TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

SYED GOLAM MAHMUD

AN OVERVIEW OF PROTECTION TECHNIQUES FOR MICROGRID AND THE FACTORS INVOLVED

Master of Science Thesis

Examiners: Pertti Järventausta
Ari Nikander
Examiner and topic approved on January 31ST, 2018

ABSTRACT

SYED GOLAM MAHMUD: An Overview of Protection Techniques for Microgrid and the Factors Involved
Tampere University of Technology
Master of Science Thesis, 53 pages
May 2018
Master of Science (Tech) in Electrical Engineering
Major: Smart Grid
Examiner: Professor Pertti Järventausta and Dr. Tech. Ari Nikander

Keywords: Adaptive Protection, Fault Current Limiter, Microgrid

Microgrids are the emerging component of smart grid system. The power transfer losses from transmission end to distribution end are aimed to reduce due to the implementation of microgrid network at distribution level and to increase the network reliability. Microgrid is a distribution network consisting of DG technologies, which can operate in parallel with utility grid to meet the required demand. However, the main criteria to isolate microgrid from active distribution network is that, it can operate independently in islanded mode. The main challenge of microgrid is that to tackle the dynamic behavior of microgrid sources such as solar cell, wind turbine generation etc. and the fault current contribution from these sources. Fault current level also varies according to the mode of operation: grid connected mode and islanded mode. These challenges make the traditional protection schemes less effective. Hence, an advance microgrid protection techniques are required to meet the above challenges for smoother and secured operation of microgrid.

In this thesis, an extensive literature review is presented about microgrid and its protection. The impact of embedded DG units in microgrid network is analyzed and their role towards network protection is presented in this thesis. There are certain impacts such as LOM, sympathetic tripping etc. which are found from research work that need to be addressed to ensure proper protection of microgrid. One of the key findings of this research is that there are several key factors affecting to design and implement an effective microgrid protection technique. The key factors include microgrid topology and type, type of DG unit, relay type, communication type and type of faults in microgrid. Then the thesis focus on different protection strategies of microgrids based on above key factors. A communication assisted adaptive protection strategy is analyzed in detail among them. It is found from the research that adaptive protection provides accurate and secured protection with advanced facilities. Moreover, a literature based case study is presented at the end of this thesis to prove the effectiveness of adaptive protection strategy in microgrid network operated in both grid connected and islanded mode.

PREFACE

First of all, I am very much grateful to my creator (ALLAH). Then, I am remembering my parents and their infinite contribution in my life which is not returnable by giving only thanks. A special thanks goes to my wife, for her support and patience during my hard time.

This thesis has given me the opportunity to build up my knowledge about subject matter. My respected thesis supervisors are Professor Pertti Järventausta and Dr. Tech. Ari Nikander. I will always remember their support and contribution to accomplish my thesis work. I feel honored during my thesis process to work with these two skilled gentlemen's.

I am a part time employee of ISS Palvelut Oy, Finland which secured my livelihood in Finland. Thanks to my work supervisor, Anja Elangwe for her cooperation.

Finally, A big thanks goes to Tampere University of Technology (TUT) for giving me chance to study here. Their administrative support and academic structures are excellent.

Tampere, 23.05.2018

Syed Golam Mahmud

CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Alternating Current
AFD	Active Frequency Drift
CB	Circuit Breaker
CERTS	Consortium for Electric Reliability Technology Solutions
DC	Direct Current
DG	Distributed Generation
DNO	Distribution Network Operator
DER	Distributed Energy Resources
DS	Distributed Storage
EMM	Energy Management Module
EU	European Union
EV	Electric Vehicle
FJ	Frequency Jump
FCL	Fault Current Limiter
HIF	High Impedance Fault
HRDS	High Reliability Distribution System
IED	Intelligent Electronic Device
IIT	Illinois Institute of Technology
IIDG	Inverter Interfaced Distributed Generation
IGBT	Insulated Gate Bipolar Transistor
KERI	Korean Energy Research Institute
LC	Local Controller
LV	Low Voltage
LIF	Low Impedance Fault
MCC	Microgrid Central Controller
MMT	Minimum Melting Time
MCCB	Molded Case Circuit Breaker
MO	Market Operator
MV	Medium Voltage

NDZ	Non-Detection Zone
NTUA	National Technical University of Athens
OCR	Over Current Relay
PD	Protective Device
PCC	Point of Common Coupling
PCM	Protection Coordination Module
PLC	Power Line Carrier
PLL	Phase Locked Loop
ROCOF	Rate of Change of Frequency
SFS	Sandia Frequency Shift
SVS	Sandia Voltage Shift
SCADA	Supervisory Control and Data Acquisition
SRCU	Supervisory Remote-Control Unit
TCT	Total Clearing Time
THD	Total Harmonic Distortion
VT	Voltage Transformer
VSC	Voltage Source Converter
WAM	Wide Area Measurement

1. Introduction

In traditional power grid, power is produced centrally and then dispatched through long transmission and distribution lines to the customer premises. In this case, power flows from generating units to customer level and it is unidirectional in the distribution network. At present, rising load consumption and demand, advances in renewable energy sources, inadequacy of fossil fuels and growing concerns on green house gas emissions have driven to a modern pattern of power generation at the distribution network. These technologies are known as Distributed Generation (DG) [1,2]. The induction of DG sources at the distribution network causes decrease in the power transfer pressure on the distribution and transmission networks [3]. These modern technologies have enabled also the smaller distribution networks named microgrids [4,5]. The introduction of microgrid at distribution level decreases the overall operational load of the utility grid.

Distributed Generation (DG) are small scale power generation sources such as diesel generator, a fuel cell, gas turbine, micro turbine, wind turbine, battery storage, photovoltaic cell etc. These DG resources with storage devices and controllable loads create a distribution network called microgrid. The operating modes of microgrid are islanded mode and grid connected mode. Microgrid can operate independently known as islanded mode of operation, during a fault or in case of any disturbances in the main network. This feature mainly isolates the microgrid from active distribution network. On the other hand, it operates also in grid connected mode in normal condition. To increase the reliability and efficiency of the microgrid, the DG sources in the microgrid are combined in a plug-and-play model and they work in peer to peer manner [35]. The DGs can be placed in any part of the microgrid network due to plug-and-play property without changing its controls and peer-peer operation mode discard the necessity of master controller unit.

However, despite their advantages, microgrids encounter many technical challenges related to control and protection due to high penetration of DG resources. The most noticeable challenges faced by microgrid network includes:

- Bidirectional power flow in the power grid
- Dynamic behavior of DG sources
- Topological changes in the microgrid network
- Low level fault current during islanded mode
- DG type (direct fed DG or inverter fed DG)
- Number of connected DG in the distribution network

The aforementioned reasons make the traditional protection schemes less effective for an microgrid. Hence, appropriate protection scheme is very much important to make sure safe and reliable operation of microgrid both during islanded and grid connected mode.

1.1 Statement of problem and thesis objectives

There are three important challenges that have to be considered in order to implement a feasible protection plan for a microgrid. First, the protective relay should conduct with low and high level of short circuit fault current in islanded and grid connected mode respectively. Second, the protective relay should sense the direction of fault current and operate properly in case of bidirectional power flow within microgrid. Third, the available protection schemes should operate quickly to identify the fault due to the high penetration of inverter interfaced DG (IIDG) and their intermittent nature in the microgrid. IIDG's are very sensitive to network disturbances specially when operating in islanded mode.

The above-mentioned issues can be solved by relay coordination establishing communication link between different relays and a microprocessor based central processing unit. The central processing unit are capable to change the relay settings based on the status of microgrid and identify the faults as the unit can access the measurements throughout the entire microgrid. However, there is chance that communication system may fail, so that microgrid protection schemes may not operate effectively. Therefore, a local measurement-based protection scheme must be developed for the stable and continuous operation of the microgrid.

The main objectives of this thesis by considering aforementioned issues are as follows:

- Literature review of microgrid concept in general and case analysis of various microgrids implementation around the world.
- Discussion on the impact of DG and different key factors involved in designing an effective microgrid protection scheme.
- Most importantly this thesis aims to study and analyze available protection schemes for microgrids. The target of this part is to find out a general protection scheme which is suitable for short circuit fault and both operating modes of microgrid. The effective protection scheme will be recommended further by considering all technological issues.
- The effectiveness of the microgrid protection scheme is proposed by a literature case study implemented in USA.

1.2 Structure of the thesis

The thesis has seven chapters organized as follows:

- Chapter 1 provides an introduction of the thesis. The main objectives of the thesis are presented in chapter 1.
- Chapter 2 of the thesis gives an extensive overview of the microgrid network. This chapter begins with a detailed introduction of microgrid architecture and its properties. Control and protection of microgrid are also discussed in this chapter. The concepts are recently developed and may vary around the various parts of world. So, existing microgrid cases are also presented at the end of this chapter.
- The various challenges faced by microgrid network at the existence of DG resources are discussed on chapter 3. This chapter gives an information about DG impact on fault protection.
- Chapter 4 focuses on different key factors involved in designing an effective microgrid protection scheme e.g. type of DG resources, relay type etc.
- Chapter 5 of the thesis concentrate on the microgrid protection. Available microgrid protection schemes are discussed with a special attention on adaptive protection. The target of this chapter to present an effective microgrid protection schemes in various aspects.
- In chapter 6, a literature based case study is presented to prove the effectiveness of adaptive protection strategy in microgrid network operated in both islanded mode and grid connected mode.
- Finally, chapter 7 concludes the entire thesis work with future recommendations.

2. Microgrid Concept and Its Implementation

Microgrid is one of the exciting research area in the field of power engineering. It consists of several concept such as control and protection, network operation, distributed generation (DG), renewable energy sources (RES), power electronic converter etc. Consequently, it is very common to notice that more researchers are interested to work with microgrid network nowadays and more literature work have been done in past. Microgrid concept, control of microgrids, protection coordination and few realistic microgrid implementation around the world are the main topics to be covered in this chapter.

2.1 Microgrid structure and properties

It is highly challenging to define microgrid with a concrete statement that is unique and can be used broadly everywhere. For example, Lasseter define the microgrid as a system approach by considering loads and DG sources as a subsystem [6]. This view of Lasseter overcome many problems of individual use of DG unit. In 2006, Smart Grids, European Technology Platform introduce the microgrid as a low voltage network consist of DG units, energy storage devices and controllable loads that can operate independently or in parallel with distribution network on demand [7]. Further, Laaksonen in his PhD thesis define the microgrid as an island operated distribution network to reduce outages and become one of the key part of smart grid [8].

Microgrids are mainly size independent and defined by their function. There is no specific information available about globally accepted maximum or minimum size of microgrid. Although, the size and structure can alter broadly, microgrids are usually seen as a small part of low voltage (LV) or medium voltage (MV) distribution network with controllable loads where local sources are also participated in power production. The operation of microgrid can be either in islanded or grid connected mode based on several factors such as grid outages, preplanned disconnections or economical aspects [9]. Microgrids have different functions and architectures compared to traditional distribution network which does not have island capabilities and self-autonomy.

However, from the above discussion, the basic idea of microgrid is to sum up and integrate loads and distributed storage (DS) with distributed energy (DG) in distribution network mainly near the consumer end for power optimization with the following operational conditions and functionality [9]:

- Sufficient amount of power production to fulfill the required demand by end users.
- Proper power management including power quality monitoring, voltage dip compensation, reliability of the network.
- Plug and play properties where a new source can be connected to the network immediately and during islanding there are enough power to reduce outages.

In this section, components of a microgrid and network configurations are discussed.

2.1.1 Components of a microgrid

A number of diverse technologies are aggregated and integrated together to form a microgrid network. First, these technologies are a combination of distributed generation (DG), distributed storages (DS) and loads. Second, a physical connection must be established between DG, DS and loads. Finally, control and protection components are required to ensure proper energy management and reliable operation of the microgrid network.

Distributed Generation (DG) units are the main components of a microgrid which includes sources like photovoltaic cells, wind turbines, fuel cells, rotating machines etc. DG sources can be divided into two sub categories depend on their connection device: traditional synchronous generator-based DG (SG-DG) and inverter interfaced DG (IIDG). Synchronous generator-based DG units are connected directly to the network and IIDGs such as solar arrays, fuel cells are connected through power electronics converter in AC medium. Distribute Storage (DS) components are essential feature of microgrid and mainly used as a backup source in the network during power shortage. Storage device includes high power batteries, super capacitors, flywheels, compressed air systems etc. DS increases the reliability of microgrid network by operating in parallel with DG units. This technology enables to mitigate the intermittent nature of DG sources like solar and wind. Nowadays electric vehicles (EV) are also employed as a feasible alternative of storage devices. Microgrid loads are controllable in nature based on demand to supply. Some loads are critical to be provided by continuous supply of electricity. On the other hand, rest of them are non-critical loads. Load demand may vary depending on customer type such as industrial, commercial and residential consumers.

The physical network that mainly establish a connection between microgrid with main utility grid and inside of microgrid network among distributed storage, distributed generation and critical/non-critical loads. The power transfer takes place in the overall network through physical connection. Either overhead conductors or underground cables may be used to distribute powers throughout the entire network.

An effective control and protection system is necessary in order to ensure the proper operation of DG units together with controllable loads and storage devices. This issue demands the need of both software and hardware control systems such as the use of Intelligent Electronic Devices (IED) to monitor, detect, isolate and restoration the network fault. IEC-61850 standard may be used to establish a communication link between microgrid components. AMR meters can be used at customer end to facilitate the service.

Figure 2.1 depicts a typical microgrid network that embeds a wind turbine, a DC solar system, traditional synchronous generator and a battery bank as storage unit. The generation from solar and wind are connected to the network through power electronics converter, whereas AC produced by synchronous machine is directly fed to the network. The microgrid is connected to main grid through a switch and the connection point refers to point of common coupling (PCC). The above system may operate in parallel with utility grid when switch is closed at bus 1 and on the other hand microgrid may be disconnected intentionally or unintentionally which enables island mode of operation.

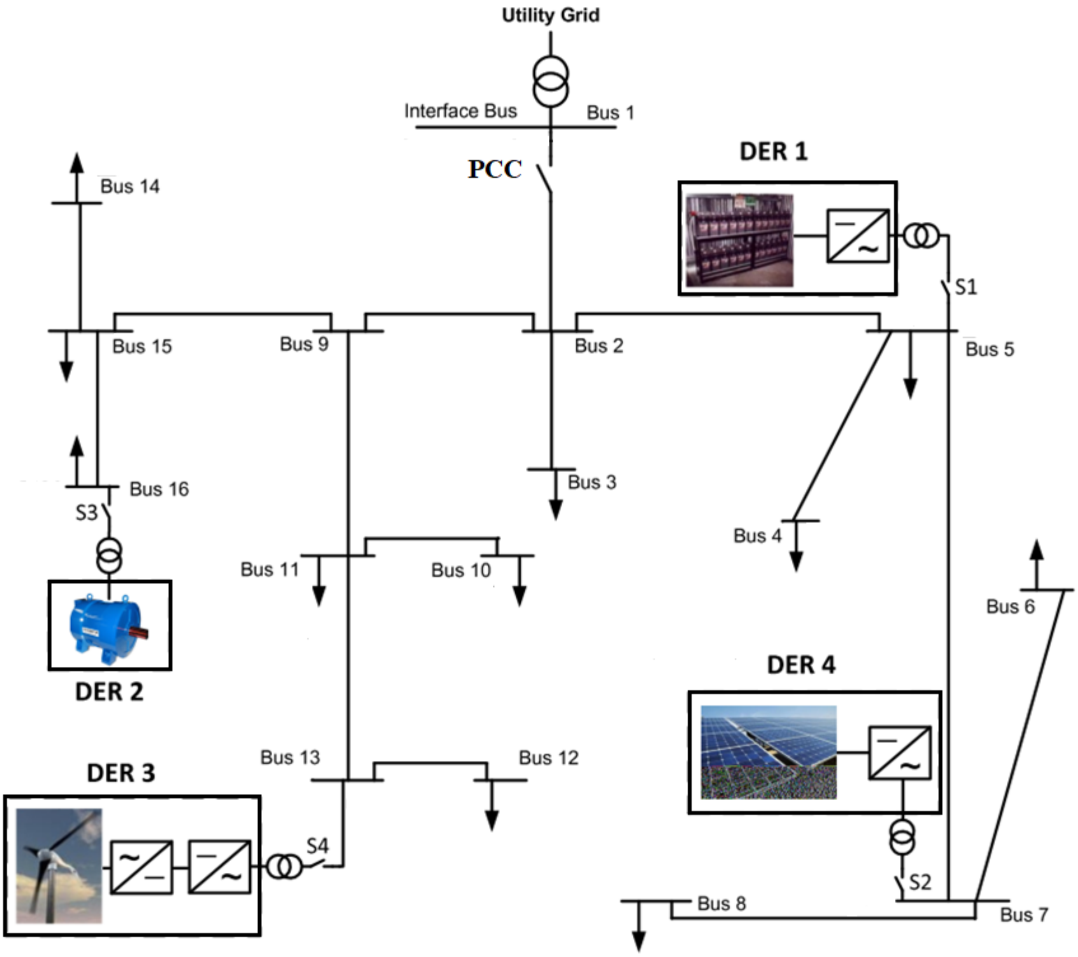

Figure 2.1: *A sample diagram of a microgrid with DG, DS and Loads.*

2.1.2 Network configuration

The microgrid components described in section 2.1.1, can be connected in three different ways shown in figure 2.2. The three possible network configurations are radial, ring and mesh connections. The network configuration layout implemented are based on source type, geographical location and voltage levels. A radial connection among microgrid components is simple and easy to implement it. This configuration also need easiest protection plans. Ring topology is more complicated than radial configuration as it provides multiple path for flow of current. Protection strategy also require advance features. The most complicated topology is mesh configuration. This configuration has multiple connection between microgrid components thus have multiple options of power distribution. This complex architecture requires a comprehensive protection techniques to ensure reliable operation of microgrid.

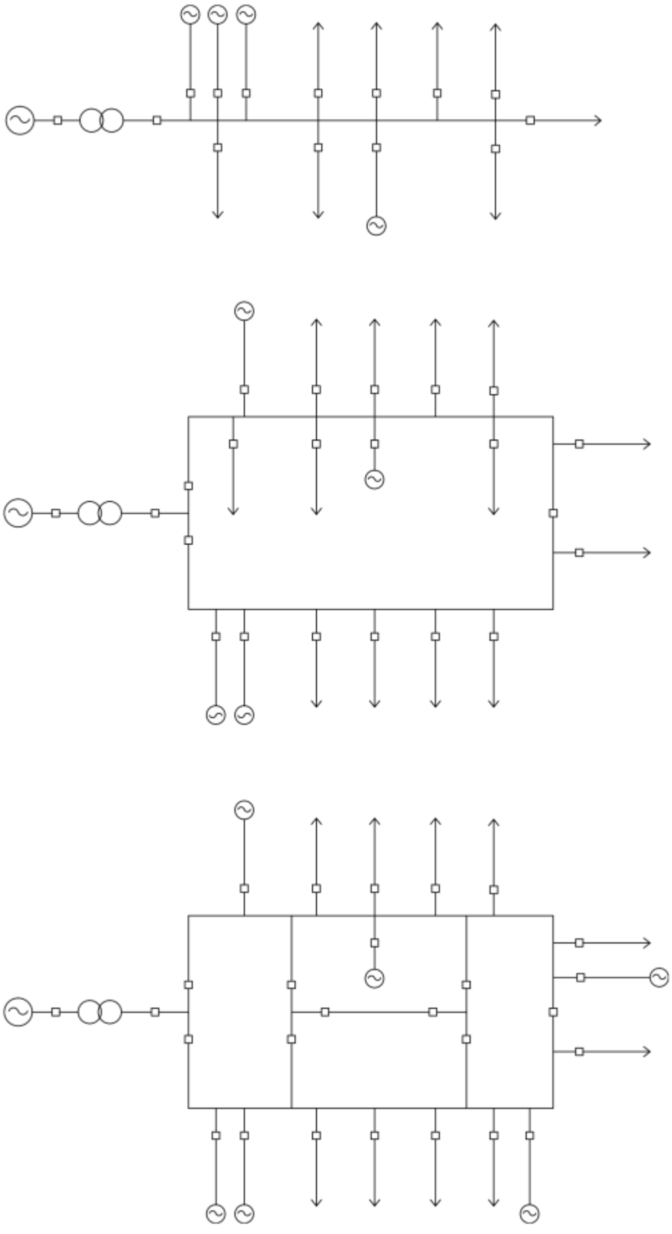

Figure 2.2: *Radial, ring and meshed network configuration from top to bottom [10].*

2.2 Control of Microgrids

A microgrid may have several DG unit connected or disconnected from the grid, intentional or unintentional islanding may occur, or there is less power generation which further leads to a frequency instability due to higher power demanded by the loads. The main responsibility of microgrid control system under any condition mentioned above is to ensure continuous supply of electrical power to the loads and to increase the reliability of the network. The controllable variables are frequency, voltage, reactive and active power [11]. The value of above variables changes based on microgrid mode of operation. During grid connected mode of operation, grid following control scheme are applied. This means that the microgrid frequency and voltage are maintained by utility power grid. Hence, the real and reactive power of the microgrid are regulated by the microgrid controller. On the other hand, grid forming controls are employed during islanded mode of microgrid operation. In this case, the main obligation of microgrid controller is to maintain frequency and voltage in addition to reactive and real power management within the microgrid network. Local controllers (LC) are doing the power balance in the network with the help of central controller via a secured and fast communication link [11].

These control strategies are implemented through supervisory control that include centralized control and decentralized control. Both control scheme includes (i) Microgrid Central Controller (MCC), (ii) Market Operator (MO), (iii) Local Controller (LC) linked with (a) storage unit, (b) load (LC_{load}) and (c) DG units (LC_{DG}) [11]. LC_{DG} is responsible for generation management and LC_{load} is responsible to ensure reliable power supply to consumer end in microgrid. Distribution network operator (DNO) monitor the multiple microgrid simultaneously. The brief discussion of supervisory control is presented in next subsections.

2.2.1 Centralized control

There is a look up table maintained by microgrid central controller (MCC) in centralized supervisory control scheme. The information of look up table updated in every predefined interval with respect to type of DG, real time status of DG (OFF/ON), generation by DG, voltage and current levels at relay points, network demand (load), and mode of operation (islanded or grid synchronized mode).

The MCC has two important modules: Protection Coordination Module (PCM) and Energy Management Module (EMM). The PCM mainly responsible for protection of the microgrid both in grid connected and islanded mode of operation. The main purpose of this module is islanding detection and fault current measurement. After this appropriate protection settings should apply by PCM to stable the microgrid network and utility grid. In general, adaptive protection strategies are applied in order to meet the dynamic changes in the microgrid network. EMM is mainly responsible for monitoring active and reactive power, voltage and frequency of the microgrid network. The EMM provides the operating values to local controllers (LC). The central controller performs the following operation during grid connected mode:

- Monitoring of above discussed system parameters from bus, load, DG unit whichever needed for specific control.
- Active and reactive power control in most economic way of the DGs.
- Ensure secure and reliable operation of the network and maintain synchronism with the host grid.

The task of central controller is different than before in case of islanded mode and is listed below:

- Voltage and frequency control command issue for master DG unit and, real and reactive power control command for other operating DG units.
- A tripping signal issue for load controllers to disconnect the loads except critical loads based on the backup reserves and load criteria.

The implementation of centralized supervisory control scheme requires a comprehensive communication between local controllers and microgrid central controllers. This large communication architecture is sometimes infeasible for massive areas. The entire control system may fail even though a small fault exists in communication link [11].

2.2.2 Decentralized Control

It is impractical to employ centralized control scheme in remote areas due to large distance between DG sources. In addition to this, it requires extensive communication structure which demands higher cost. In such cases, decentralized control schemes for microgrid has been developed to overcome above problems. These decentralized control system enables to connect more number of DG units which are owned by different service providers.

Local controllers are more responsible and must perform more functionality in decentralized control schemes compared to centralized control scheme. Due to this, DGs and loads have more autonomy to operate. The hierarchical structure of the decentralized control scheme is similar to centralized control scheme which includes LC, MCC and DNO. The prime function of LC includes supply the maximum possible production to meet the demand and enhance the total performance of the microgrid. Here, each inverter coupled DG units are controlled independently for power sharing. Voltage and frequency of the microgrid are maintained by main grid during grid connected mode. The DG is modeled with droop control for load sharing which is most popular control scheme. In grid connected mode, the main concern is to provide real and reactive power to the microgrid network. Hence, reactive power sharing is controlled by voltage droop and similarly real power sharing is control by frequency droop. Figure 2.3 shows the droop characteristics curves of real and reactive power as $f=f_{max}-m(P-P_{max})$ and $V=V_{max}-n(Q-Q_{max})$ respectively [11] [12], where V_{max} and f_{max} are the DG unit maximum voltage and frequency, voltage droop and frequency droop coefficients are n and m, P and Q are the instantaneous value of real and reactive power.

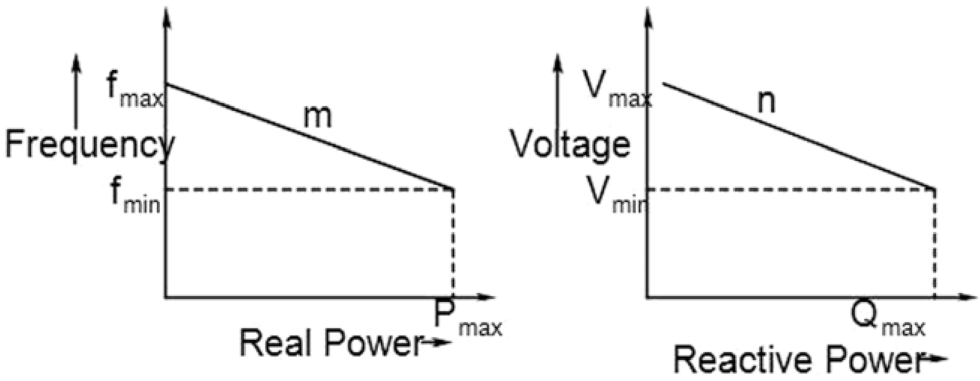

Figure 2.3: *Real and reactive power droop characteristics curve [11].*

During islanded mode, one of the inverter fed DG is mainly responsible for frequency and voltage control of the microgrid network. These responsible DG unit is known as master unit which control strategy refers to only control voltage and frequency. The rest of the DG sources are provided real and reactive power to the microgrid load. Local controllers (LC) gets information from MCC about amount of load to be served and rest of them to be disconnected.

The main limitation of decentralized control system is that microgrid central controller is not aware of all actions taken by local controller as more emphasize is given to local controllers. Even a task performed by specific LC is unknown to other LCs of the microgrid network. To overcome this problem, a hybrid control system is required where MCC recheck the control commands issued by LC to detect any lack of control.

2.3 Protection of Microgrids

Traditional distribution networks are designed in such a way that to operate radially. That means power flowing from generation point to customer end through radial feeders. This less complex radial architecture also makes the protection system of the distribution network simple and straightforward. Thus, protective instruments such as over current relays, reclosers and fuses are mostly used to protect conventional distribution networks [12]. The traditional protection strategies for over current radial feeder faults are largely affected due to the connection of new distribution network known as microgrid. So new protection strategies are employed and it must be ensured the risk-free operation of microgrid in both modes. Therefore, the protection challenges must be addressed to design an effective protection scheme linked with both modes of operation. In the next subsections, conventional protection strategies are firstly discussed, then the issues associated with microgrid networks are introduced in short.

2.3.1 Traditional protection coordination

As it was mentioned in earlier section that reclosers, fuses and inverse time overcurrent relays are widely used in distribution network protection purpose. Fuses must be maintained in coordination with a recloser placed at the middle or beginning of the feeder. Both protective devices should work in coordinated way. A fuse is responsible to conduct only when a permanent fault occurs in a feeder known as fuse saving scheme [12]. However, the reclosers operate if a temporary fault exists in the feeder and isolate the faulty feeder by being open (fast mode). In this stage, reclosers try to clear the fault without having major disturbances in the network. The reclosers will operate as a backup in its slow mode in case of fuse failure to isolate permanent faults in distribution network [12]. The feeder relay will provide main back up protection in case of both recloser and fuse failure.

Figure 2.4 illustrates the idea of the traditional coordination of fuses, reclosers and relays in a typical distribution network [12]. The figure 2.4 represents that the coordination among protective devices are arranged for all fault currents between I_{fmax} (maximum fault current of the feeder) and I_{fmin} (minimum fault current of the feeder) in such a way that, the recloser's fast characteristic curve lies under the fuse minimum melting time (MMT) characteristic curve, whereas the recloser slow characteristic curve lies over the fuse total clearing time (TCT) characteristic curve. Hence, the reclosers are opened to clear the temporary faults by themselfs before the fuse starts to work and melt. However, a permanent fault is cleared by a fuse immediately before a recloser starts to clear it in recloser slow mode. The figure 2.4 also tells that, a protective relay is responsible for overall backup protection as its characteristics curve lies above all other protective devices characteristic curves.

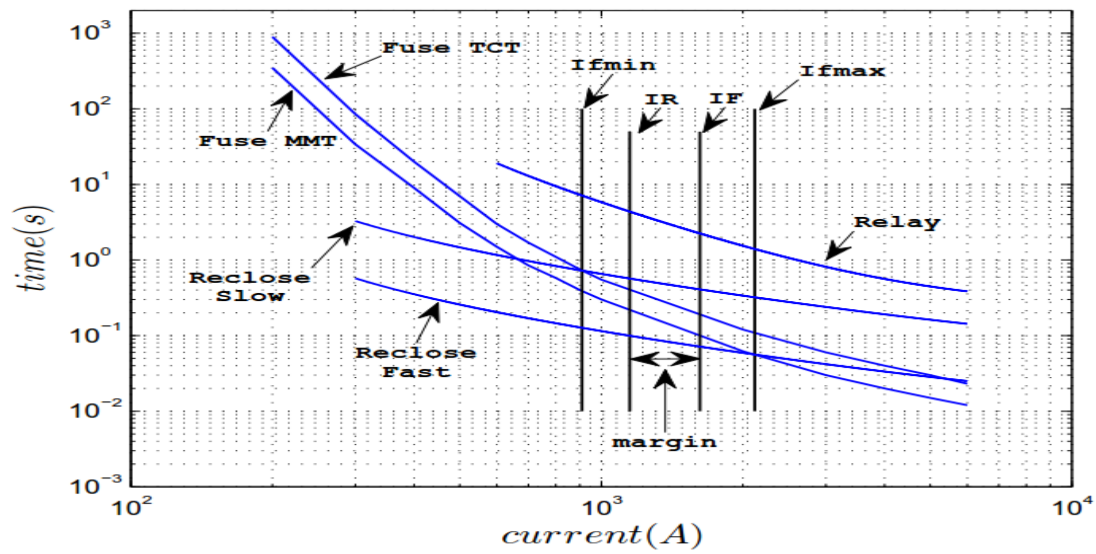

Figure 2.4: *Traditional coordination of fuses, reclosers and relays in a typical distribution network [12].*

The fault current flowing through protective devices must be in between I_{fmax} and I_{fmin} for the coordination among relays, reclosers and fuses. It is also necessary that fault current passing through protective devices are almost equal. That is also important for coordination between reclosers and fuses that fuse fault current and recloser fault current remains within margin as indicated in figure 2.4.

Typically, a fuse has two characteristic curves: Total Clearing Time (TCT) curve and Minimum Melting Time (MMT) curve. The MMT defines the period between when a fuse starts to melt and the overcurrent inception, whereas TCT defines the total duration passed from the starting of overcurrent condition to the feeder disconnection. The following exponential function gives the characteristic curve of fuse [12].

$$t_f = \exp\left[\sum_{n=0}^{k} a_n \ln^n\left(I_f\right)\right] \tag{2.1}$$

where t_f is TCT or MMT, polynomial order k and I_f is the current magnitude. Curve-fitting exercise method is used to determine the value of coefficient a_n.

The inverse time characteristics curves of relays and reclosers are obtained from following equation given below [12].

$$t_{op}(I) = TD\left[\frac{A}{\left(\dfrac{I}{I_{pick-up}}\right)^p - 1} + B\right] \tag{2.2}$$

Where TD is the time dial setting, t_{op} is the operating time of device, $I/I_{pick-up}$ is the ratio of device current to device current set point and *A, B, p* is constant.

Figure 2.5 shows the steps of traditional reclosing technique [13].

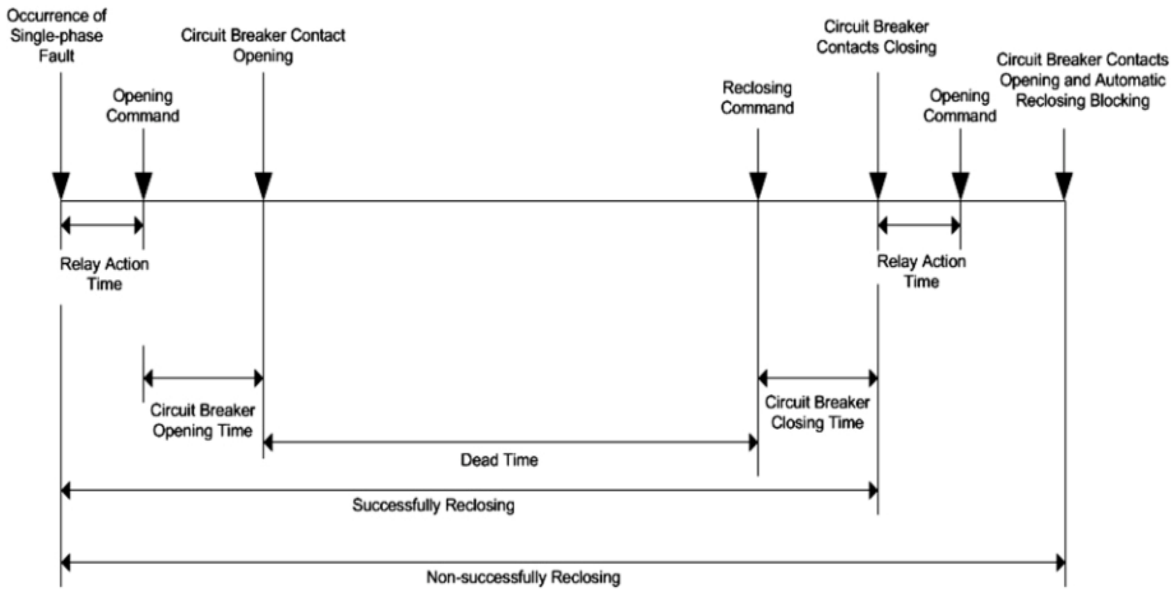

Figure 2.5: *Traditional reclosing technique [13].*

2.3.2 Protection in Grid connected mode

Traditional over current protection system can be employed for grid connected microgrid due to larger fault current exist in the presence of main grid. However, due to the presence of DG in distribution network, there is structural change in the radial network and even the network parameters may change. Hence, it is also affected the protection system partially or there is loss of total protection system. The coupling of DG sources in a downstream part of radial feeder may (i) change the limit of maximum (I_{fmax})and minimum (I_{fmin}) fault current of the feeder, (ii) upstream protective devices has less fault current compared to downstream protective devices and (iii) cause bidirectional power flow in a feeder [12]. Thus, multiple challenges associated with protection scheme may arise depending on DG type, DG size and DG location in a network. The main challenges come forward due to the introduction of DG sources in a distribution network comprise, "dynamics in fault current magnitude", "prohibition of automatic reclosing", "unnecessary disconnection of DG unit" and blindness of protection. These issues are discussed in detail on chapter 3.

2.3.3 Protection in Islanded mode

Electronically coupled DG sources are connected to the network via power electronics converter. As power electronics switches are low current drive devices, they should be protected against overcurrent condition. This in turn to causes low fault current by converter connected DG. The fault current contribution in islanded mode are insignificant compared to microgrid operated in grid connected mode. Moreover, the power generating from rotating machine are very high compared to converter connected renewable energy sources such as solar, wind power. Microgrid operated in islanded mode have less fault current due to presence of small scale power sources. Consequently, the traditional overcurrent protection techniques are not effective solution for microgrid running in islanded mode. Therefore, an effective protection schemes are needed for island operated microgrid.

2.4 Review of protection schemes for Microgrids

Bidirectional power flow, fault current level, faster and accurate operation of protective devices are the most critical issues need to be address by protection techniques of microgrids in islanded and grid connected modes. The stability must be maintained after protection for microgrid operating in islanded mode and for sensitive loads. Several microgrid protection methods have been proposed [14-31].

A protection strategy was proposed by Lasseter and Nikkhajoei [15] for single line to ground faults and line to line faults in a microgrid using zero sequence and negative sequence components of the line current. Detection of high impedance fault in a microgrid was highlighted as an unsettled issue. A protection scheme was developed based on differential relaying techniques for a microgrid with inverter interfaced DG

(IIDG) sources [16]. The author of [16] has tested the technique for both unbalanced and balanced faults comprising high impedance faults. A voltage-based protection scheme by Redfern and Nasseri was developed for a microgrid [17]. In this study, authors considered both short circuit and earth faults. The authors utilize the d-q components of voltage. The value of d-q components was compared with the defined reference value of d-q components. This paper does not provide any clear idea about protection system in case of unbalanced load or a high impedance fault in the system.

There are a lot of research have been done based on communication assisted relays [18,19,22-26]. An adaptive protection scheme was proposed by Sukumar and Adly [23]. However, the scheme is not well suited for low DG penetration. It is also noted that the author of this paper does not verify the effectiveness of the method in islanded mode of microgrid operation including IIDG sources. A protection method for medium voltage grid with IIDG was developed using microprocessor-controlled relays [22]. In this method, a wireless local area network link is established between relays to communicate each other and with central controller. Protection control strategy was developed based on negative sequence component of current and over current method. The same strategy was also proposed in [21] for a low voltage microgrid. But an additional protection strategy was added in [22] to detect high impedance fault in network using third harmonic current component. The authors also focused on backup protection in case of communication failure between protective devices. A communication assisted protection strategy for medium voltage looped microgrid configuration was proposed in [26] and similar protection method applied in [22]. The main advantages of proposed protection scheme in [22] and [26], are independent of the position of DG sources, short circuit fault current level, size and operational mode of microgrid. However, communication plays a vital role in both protection strategy.

Protection of microgrid based on IEC 61850 protocol has been developed [24]. The overcurrent relays of the network connected through centralized communication assist controller. The tripping values of over current relays are calculated dynamically and they are stored in central microgrid controller. The test network used in [24] contains synchronous generator and IIDGs. This research work does not contain any information about the performance of proposed protection method for balanced and unbalanced faults. This method is neither applicable for high impedance fault. The protection system described in [24] was further improved by adding backup relays to the network [25]. The relay settings are defined based on dynamic calculation using network operational parameters and latest relay settings are used in case of communication failure. There is only discussion about three phases to ground faults and authors has not analyzed the protection method in case of several types of faults inside microgrid network.

A protection technique was proposed for island operated microgrid including inverter coupled energy sources [27]. The system protective devices do not rely on communication. Current limiting method is used to disconnect the inverter during faulted condition. There was no test case to validate the effectiveness of proposed protection strategy. In [28], a relaying strategy using differential energy was proposed for a radial and looped structure microgrid network. The test cases are validated for both grid connected, and island operated microgrid. In this paper, authors proposed a model to detect high impedance faults. The results from simulation study validate the effectiveness of proposed protection plan for symmetrical and unsymmetrical faults. A current and voltage control-based protection plan was proposed for low voltage IIDG contained microgrid network [29]. In this study protective relay settings must need to be changed between islanded and grid connected modes. A flywheel-based protection system was designed for island operated microgrid [31]. Traditional over current relays are less effective in island operated microgrid network due to lower level of fault current. The proposed protection strategy based on flywheel provide the additional fault current thus traditional over current relays can detect the fault and trip. However, additional investment needed for this protection plan due to flywheel connection and operational complexity of the network also increases.

2.5 Examples around the world

The number of microgrid implementations and ongoing experiments are increased day by day throughout the entire world. The study of microgrid implementation and ongoing research will help to understand the microgrid operation smoothly. Diverse topologies and technologies have been studied for various tasks. Some of the researches are only for R&D purposes, however others are implemented in grid connected or islanded mode. The research objective has a very wide span due to the versatility of microgrid concept. Microgrid cases around the world are discussed in this section of thesis.

2.5.1 European Union

Climate change awareness is at very high level in European Union and there are specific goals that must be fulfilled by the EU member states by 2020. European Parliament has approved various directives such as 2001/77/EC, 2003/30/EC and 2006/32/EC. These directives have certain targets such as the reduction of carbon emission, increase the energy market share of renewable energies, less energy consumption and increased efficiency [32]. Accordingly, EU has announced incentives plan, so that several research projects going on member states.

"Microgrids Project" was the one of first funded project by European Union and it was handle by a consortium guided by National Technical University of Athens (NTUA). The objective of this project was to analyses the dynamic behavior of DG unit in microgrid and develop ideas for multiple issues such as protection strategies, control algorithms, black start techniques, DER interface response, reliability benefits as well as intelligence requirement [33]. The Kythnos Island Microgrid, Greece, is one of the pilot installation run by NTUA. The other pilot demonstration sites are Continuon Holiday Camp, Netherland and MVV Residential Demonstration, Germany [33]. A detailed analysis on control methods of microgrid was done in ISET microgrid, Germany [34].

After successful completion of initial projects, a further continuation of project was again undertaken by a consortium led by NTUA and it was named as “More Microgrids Project”. The new objective was to develop alternative methods, universalization strategies along with plug and play concept of microgrid sources [33]. A comprehensive study based on new objectives was performed in Mannheim-Wallstadt, Germany.

Other small scale microgrid installations include the Frielas Feeder in Portugal, Labein Microgrid in Spain, CESI Microgrid in Italy [34].

2.5.2 North America

The Consortium for Electric Reliability Technology Solutions (CERTS) is the most familiar microgrids of USA, illustrated in figure 2.6. It is a partnership project between the University of Wisconsin, Sandia National Laboratories, Northern Power Systems, S&C Electric Co, TECOGEN and AEP [35]. CERTS microgrid have multiple DG sources with connected load. A thyristor-based switch is used to separate the microgrid from the host grid. The main aim of this collaboration work is to facilitate the smoother DG connection to anywhere in the microgrid network. Consequently, three important CERTS microgrid concept have been proposed and developed by the group. The CERTS microgrid concepts are to design an automatic switching system for the transition between microgrid operating modes, a microgrid internal fault protection scheme for low level of fault current and a control algorithm to fix the frequency and voltage deviation without having fast communication during faulted condition [35]. Microgrid analysis software tool was also developed by the Georgia Institute of Technology in parallel with CERTS project.

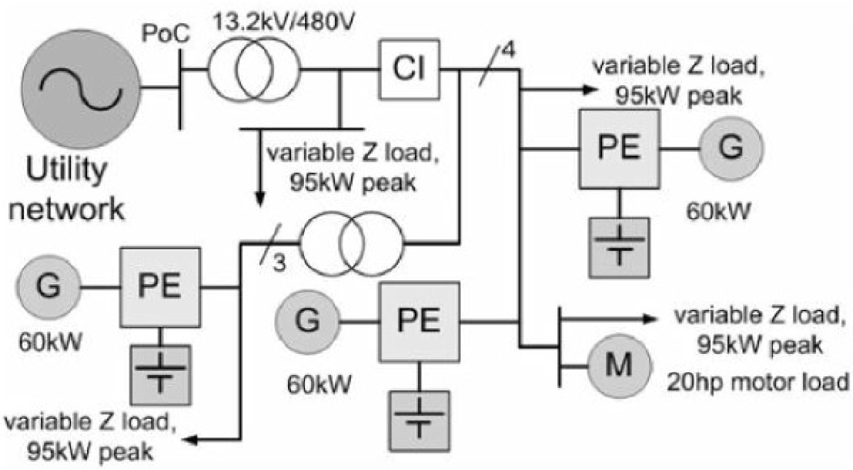

Figure 2.6: *CERTS Microgrid network [35].*

There are other R&D activities going on in British Colombia Institute of Technology Microgrid, Mad River Waitsfield by Northern Power Systems and the General Electric Microgrid [35]. The main purpose of these activities is to design and implement control and protection schemes for microgrid in various conditions.

2.5.3 Australia

Australia has no microgrid project running at this moment, but the government of Australia is more concern about research and development activity on distributed energy sources and microgrid. There are a lot of separated communities in Australia and they have huge distance between them. However, some communities have no proper transportation system, not only for road connection but also for harsh weather. That causes a new trend in electricity market of Australia to move on towards renewable energy based local power production and consumption. The development of DG based microgrid will be great incentive for service provider in terms of power transmission and distribution. The Windorah community in Queensland and The Kalumburu and Yungngora communities in Western Australia are the remote communities where microgrid network establishment is needed [35]. On the other hand, King Island in Tasmania and Thursday Island in Queensland are the islands where energy suppliers are operating microgrid [35].

2.5.4 Korea

Korean Energy Research Institute (KERI) has developed the first test system of microgrid. An extensive microgrid test system was implemented by KERI, has several components such as wind turbine and photo voltaic simulator, diesel generators, fuel cells, critical and non-critical loads. The network has power quality monitoring devices and energy storage devices. A communication assisted energy management system will be added later with this test system. The main objective of KERI microgrid test system is to study all prospects of microgrid specially control and protection as the test system has all microgrid components. Initially the capacity of test microgrid was 100 kW and it was extended further for future studies [35].

Jeju Island in Korea is very popular for wind energy production. A very small amount of wind power was available in 2006 (19 MW) but it has increased to sufficient amount of 230 MW in 2009 [35].

3. Impact of DG in Microgrid Protection

Appropriate protective devices with faster operation, better selectivity, flexibility, simplicity, low cost and equipped with different setting opportunities has to be chosen for reliable and safe operation of the microgrid network. The most important challenges appeared in microgrid protection are due to bidirectional power flow, intermittent nature of the DG sources, dynamic behavior of DG and changes in short circuit fault current. These causes make the traditional protective system less effective for microgrid containing distribution network. These challenges are focused in this part of thesis.

3.1 Dynamics in fault current magnitude

The ability of microgrid to work in two modes namely grid connected mode and islanded mode has a significant impact on short circuit level of fault current. There is significant difference noticed in short circuit level due to changing modes of operation. In the grid connected operation mode, short circuit fault current will be very high due to strong utility grid connection with additional microgrid network. As the fault current is higher, so that traditional protection schemes are appropriate in this case. On the other hand, short circuit fault current is very low in islanded mode due to absence of main grid and only the low capacity DGs feed the fault. As a result, traditional protective schemes become impractical for islanded mode of microgrid operation.

Moreover, the magnitude of short circuit fault current generated by DG depends on the type of DG sources. Synchronous type DG has more fault current contribution compared to inverter interfaced DG and the magnitude of fault current in that case is 5 times of rated current [35]. On the contrary, inverter interfaced DG provide 1.5 times of rated current [35]. Also, the renewable energy sources are very much intermittent in nature and only contribute to short circuit level when the source is in active condition. So, the dynamics behavior of fault current magnitude exists due to above conditions discussed and this issues raised the need of new protection plans which can operate in both mode.

3.2 Prohibition of automatic reclosing

Automatic reclosing means that when a fault occurs in a network, the feeder breaker is opened for a brief period and closed again. Typically, a transient fault is cleared during the deadtime of reclosing and after that normal operation of distribution network continues. In this way, prolonged interruptions caused by arc faults can be avoided as the arc amplitude falls rapidly when a short interruption in a network take place.

Distribution network is radial in structure without DG installed in any part of network. Therefore, when a relay performs the reclosing sequence, downstream part of the network is disconnected to clear the transient fault. Let us consider a fault on the feeder in the existence of DG unit. Initially, both MV network and DG unit are contributed to the fault current in parallel. Then the reclosing sequence takes place and recloser disconnects the MV network. However, DG unit continue its operation and therefore maintain a voltage in fault point (figure 3.1) if the DG unit is not disconnected during the deadtime of the reclosing. There is chance that short circuit fault current of DG unit is so small that overcurrent protection of DG unit does not trip. In this situation the fault arc remains, and the transient fault seems to change into permanent fault. Hence the customers of the network will experience a longer interruption. Figure 3.2 illustrates failed reclosing caused by DG unit (Left) and successful reclosing due to DG unit disconnection. During failed reclosing, DG unit maintains the voltage at faulted point shown in figure 3.2. The successful operation of DG unit protection system prevents further fault current feeding.

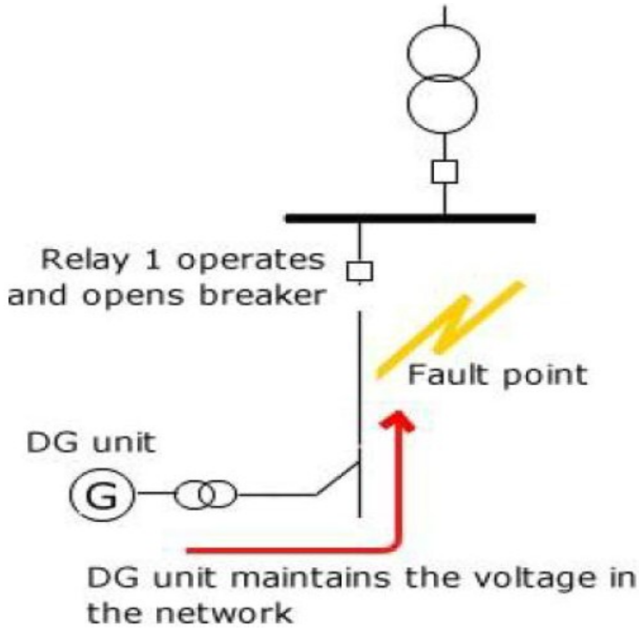

Figure 3.1: *Failure of the reclosing due to the DG unit [36].*

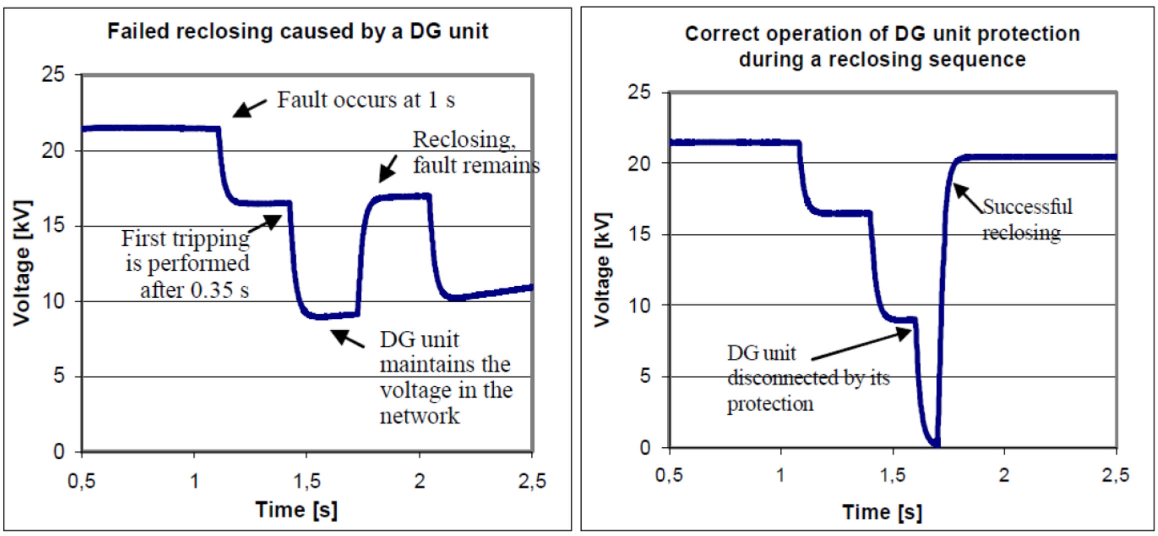

Figure 3.2: *Failed reclosing caused by DG unit (Left) and successful reclosing due to DG unit disconnection [36].*

There is some other problem which arise besides power quality impacts due to failed reclosing. Unbalanced power of the network may cause the change of rotational speed of the small-scale power unit. An asynchronous connection further developed and could be possible that damage the DG unit. Thereby the DG unit disconnection is important during the fault to prevent asynchronous connection of DG unit with main network. There must be a coordination needed between deadtime of recloser and protection unit of DG to avoid the problem discussed above.

3.3 Unnecessary disconnection of DG unit

The term sympathetic tripping means unnecessary disconnection of DG unit in distribution network. This issue is a great concern for both producer and network operator. This issue causes an unnecessary tripping of a healthy feeder; thus, customers of a whole feeder experience an undesired interruption.

This situation arises in a distribution network when a fault occurs in a feeder adjacent to DG feeder where both are fed from same substation. Let us consider a network scenario shown in figure 3.3. The fault current is supplemented by both grid ($I_{K,grid}$) and adjacent feeder DG unit ($I_{K,gen}$) towards a fault which occurs at point K. The major part of the short circuit fault current is contributed by DG unit if a large synchronous machine is placed as a DG unit and close to fault location [11]. The upstream fault current provided by DG unit flowing towards substation and further towards fault point K. This upstream current causes to exceed the reference value of the protection of healthy feeder ($Relay_1$) and hence it gets tripped before the operation of faulted feeder ($Relay_2$) [11].

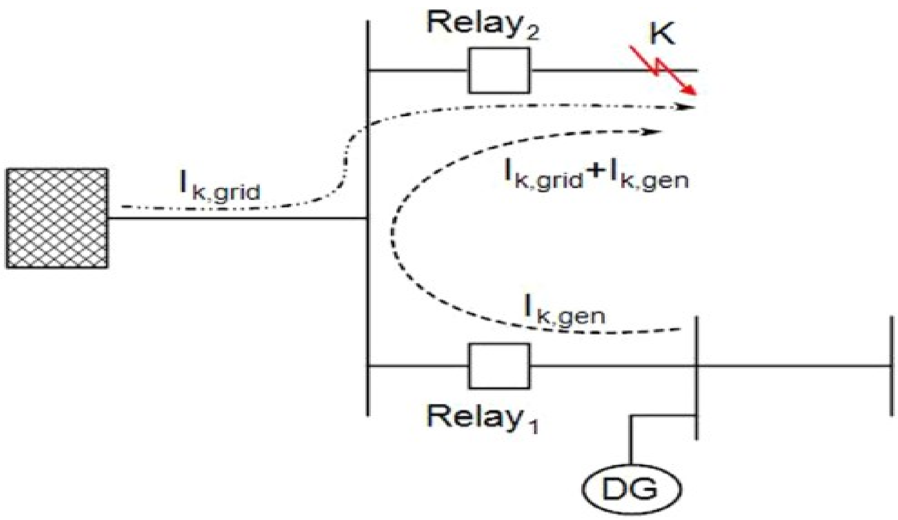

Figure 3.3: *Sympathetic tripping in distribution network [11].*

This issue needs to be addressed and proper protection plan should be implemented to avoid false tripping in a network. Unnecessary disconnection of the network can be avoided by coordinating the response time of feeder relays. That means faulted network must be isolated quickly to ensure proper operation of healthy network.

3.4 Blindness of protection

In a microgrid when a fault occurs at the lower part of the feeder both the DG unit and utility grid contribute to fault current. The network containing DG unit has increased Thevenin's impedance at faulted point compared to traditional network. The network shown in figure 3.4 is considered to analyze the impact of DG unit on fault current in a feeder. A DG unit is connected at distance d and three phase fault occurs at the end of feeder (point K). The location of DG unit expressed by a parameter l which is relative to the total feeder length (d_{tot}).

$$l = \frac{d}{d_{tot}} \tag{3.1}$$

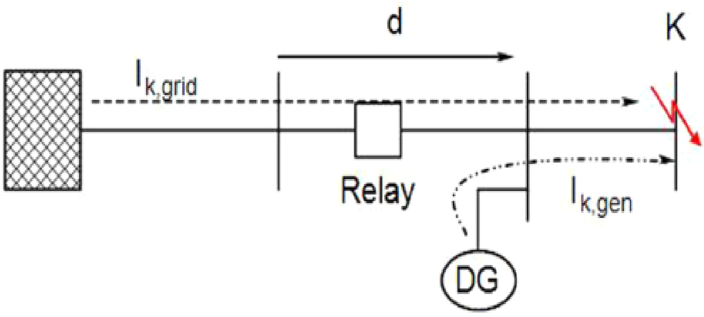

Figure 3.4: *Fault current contribution of both grid and DG unit [11].*

An electrical equivalent circuit of the above feeder is given in figure 3.5 (Left). Let Z_L, Z_G, Z_S represent the impedance of distribution line, DG unit and utility source respectively. U_S and U_G are the voltages of utility grid and DG unit respectively.

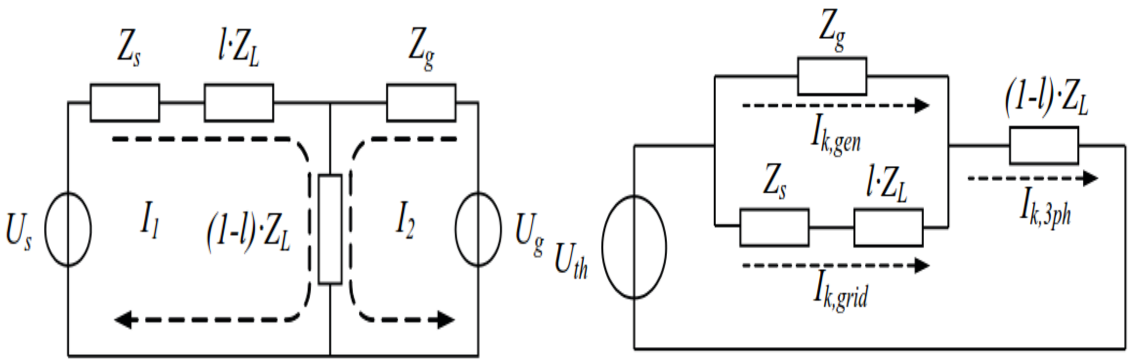

Figure 3.5: *Network equivalent of figure 3.4 (Left) and Thevenin equivalent of figure 3.4 (Right) [11].*

Thevenin's equivalent circuit of figure 3.4 is shown in figure 3.5 (Right) which is further used to investigate fault analysis and the contributed fault current by DG unit and grid. Thevenin's impedance is calculated as:

$$Z_{th} = \frac{(Z_s + l \cdot Z_L) \cdot Z_g}{Z_s + l \cdot Z_L + Z_g} + (1 - l) \cdot Z_L \tag{3.2}$$

Thus, due to the additional impedance offered by DG unit, the faulted point Thevenin's impedance is increased.
The three-phase fault current is calculated as,

$$I_{k,3ph} = \frac{U_{th}}{\sqrt{3} \cdot Z_{th}} \tag{3.3}$$

The fault current supplied from the utility grid is,

$$I_{k,grid} = \frac{Z_g}{(Z_g + l \cdot Z_L + Z_s)} \cdot I_{k,3ph} \tag{3.4}$$

The fault current contributed by the utility grid is nonlinear with size and location of DG unit. Hence, grid impedance is increased with DG impedance when fault occurs at the lower part of the feeder in a microgrid. As a result, the fault current seen by feeder relay in the network remains well below the pickup current which makes the feeder relay to unrecognized the fault and does not trip [11]. Consequently, this missing trip causes malfunction of the entire protection system of the network.

The increased feeder impedance due to additional impedance by DG unit causes to decrease the operation zone of feeder relay and arises more concern towards the proper protection system to avoid blindness of protection situations.

4. Key Factors in Microgrid Protection

The impact of microgrid features and equipment that affect its protection should be considered before proposed an extensive scheme for microgrid protection. These key factors are discussed in this part.

4.1 Microgrid type

An amalgamation of DC and AC systems generally form a microgrids. Microgrids are a combination of different types of DG units and different types of loads considering the fact that each of DG unit have an AC or DC output. In case of LVAC networks, all DG units are directly connected to AC bus bar line and then connected to the main system through power converters for their stable coupling [37]. Energy storage devices, fuel cells and solar photovoltaic arrays can be connected to the AC bus line of the LVAC networks using DC/AC inverters. Figure 4.1 shows the typical configuration of LVAC networks with DC power output (solar and fuel cell) and AC power output (wind turbine). Figure 4.2 indicates LVDC networks where DG units are connected to DC bus bar. The AC output based DG units such as wind turbines is connected to the LVDC network through inverters (AC/DC) while the DC based DG units are directly connected to point of common coupling (PCC) as shown in the Figure 4.2.

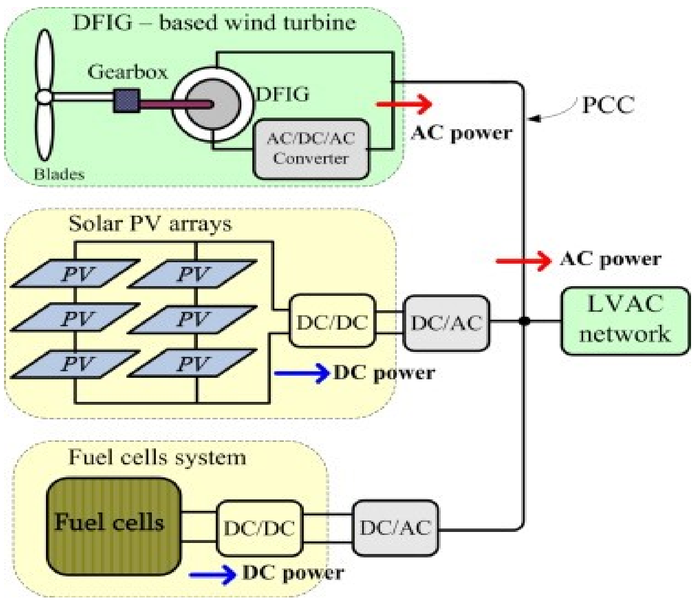

Figure 4.1: *Typical configuration of the DG units with LVAC network [38].*

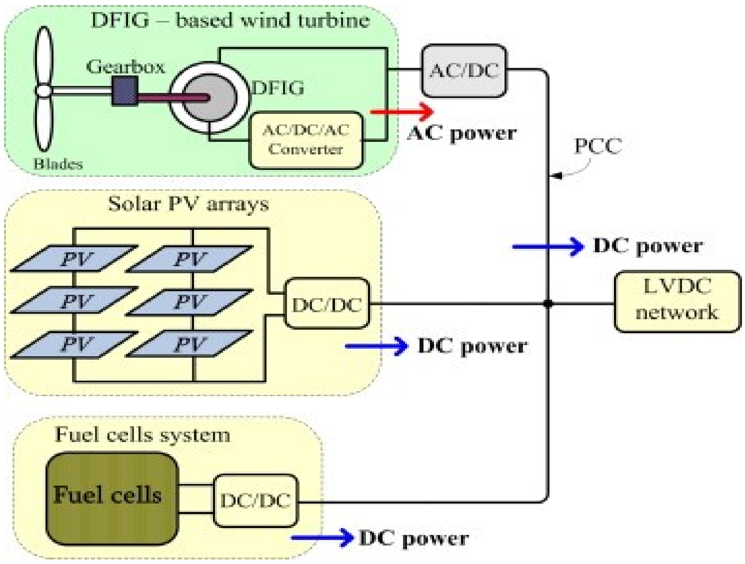

Figure 4.2: *Typical configuration of the DG units with LVDC network [38].*

The main issue in protection method of DC microgrids is lack of having a workable experience [38]. It is necessary to find out the protocols of AC microgrid protection system that can be used in DC microgrid [38]. Molded-case circuit breakers (MCCB), fuses, isolated-case CBs and low-voltage CBs are the protective devices commercially available for LVDC systems. Few of these protective devices (PD) are specifically designed for DC systems but it also can be installed in AC networks. It should be kept in mind that, the ratings for DC and AC operations are different and so that ratings must be considered during the design process of specific protection scheme [39].

Another challenging issue involved with protecting of DC microgrids is that their time constant is great and the circuit breaker operates with delay. Power electronics switch based CB's should be used for faster operation [40]. DC microgrid protection system is more challenging compared to traditional AC microgrid protection system due to fast increasing DC fault current. Adaptive overcurrent protection can be used to protect line in both AC and DC microgrids [40]. Differential protection scheme was proposed in [40] for busbar protection.

4.2 Microgrid topology

Topology is one of the important factor that control the magnitude and direction of the fault current and protection plans in a microgrid. Overcurrent relays and circuit breakers settings are determined based on grid topology. Microgrid network can be radial, looped, meshed or mixed [41], as illustrates in chapter 2 (figure 2.2). For example, a loop structure has two parallel paths and fault current is divided on that paths. Accordingly, upstream feeder protective devices measure fault current which is twice the fault current of each path within the loop network. Whereas, fault current in meshed topology is equal in downstream and upstream protective devices [41]. The research done in [42] presented a protection scheme for DC microgrid having a loop structure.

The technical implementation of protection and control of the microgrid in radial configuration is very simple and easier. Fuses are used as a primary protection equipment in radial network being not expensive protective components.

Ring configuration requires a more sophisticated protection system, but it provides better voltage stability and lower power losses [9].

The mesh grid configuration is the most complicated since it provides multiple alternative connections to all network nodes. It provides the most redundancy of the network but makes the operation and protection system more challenging [9]. Additional network nodes and protection equipment also increase the cost of the system.

4.3 Type of DG resources

There are mainly three types of DG resources which can be categorized as follows: asynchronous, synchronous and inverter-interfaced DG (IIDG). As such, their characteristics have significant impact on microgrid protection and they will be discussed next.

4.3.1 Synchronous generator

To analyze the response from synchronous generator (SG), this unit should be modeled to determine the amount of fault current generated. During normal operating condition a synchronous generator connected to a network usually run at synchronous speed with a rotor angle of δ_0 corresponding to a mechanical input power (p_m) and electrical output power (p_e). The output power transmitted to the distribution network is approximately proportional to the square of the voltage [43]. The following swing equation describing the dynamics of a synchronous generator is given below [10]:

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H}(p_m - p_e) = \frac{\omega_s}{2H} p_a \tag{4.1}$$

Where ω_s is the angular frequency, t is the time and H is the inertia constant of the rotating mass. According to above swing equation, a momentary unbalance between electrical power and mechanical power will cause generator rotor to accelerate or decelerate. Electrical output power (p_e) transmitted to the load may reduce suddenly due to the change in network voltage during faulted condition. Therefore, the difference between mechanical input power (p_m) and electrical output power (p_e) causing the SG to accelerate. The lower the voltage drops in the network during fault makes the accelerating power larger and on the other hand the longer the fault remains will cause the more acceleration of generator. The rotor angle increases with time if the fault not cleared very quickly and generator goes out of synchronism, causing a disconnection and unstable system. The maximum rotor angle should not be exceeded for smoother operation of the SG. It can be noticed from the swing equation that high inertia constant makes system more stable and synchronous generators of microgrid are sensitive to system disturbances due to small inertia constants [8].

4.3.2 Asynchronous generator (Induction generator)

The electromagnetic torque (T_e) produced inside an induction machine at any specific speed is directly proportional to the square of the voltage as follows [44]:

$$T_e = KsV^2 \tag{4.2}$$

Where s is the slip of rotating machine and K is constant depend on machine parameters.

Similarly, like SG, electromagnetic torque (T_e) is therefore reduced due to the occurrence of voltage dip in faulted situation. On the other hand, the following swing equation helps to carried out dynamic analysis of the rotor, given below [44]:

$$J\frac{dw}{dt} = T_m - T_e \tag{4.3}$$

Where J is the moment of inertia of rotating mass, w is the rotor speed and T_m is the mechanical torque applied on the rotor of the associated induction generator. It can be seen from the equation (4.3) that any reduction in electromagnetic torque due to voltage dip in the network cause the rotor to accelerate provided that mechanical torque is assumed to be constant at faulted condition. High inrush current can be produced when generator trying to restore the fault and system voltage due to the presence of magnetic field inside the airgap. Later this tends to cause a voltage drop across the connection point between induction generator and the substation which further decrease the terminal voltage of the generator.

For induction generator, it is become very complicated situation when phase to phase faults are occurred in network as it approaches towards highest overvoltage's induced by stator fluxes [45].

4.3.3 Inverter-Interfaced DG (IIDG)

The DG energy sources that produces DC output which is connected to inverter as an input and interfaced with AC network. The electronic topology of the inverter and the control mechanism of that inverter are depending on how the network is seen from the inverter. Actually, inverters are designed based on the type of network it's going to employed.

Many kinds of malfunctioning may experience by inverter of inverter based DG (IIDG) during a fault. If the control of voltage source converter (VSC) based DG units depends on constant power control, then a momentary decrease in grid voltage will increase the current of a VSC. This phenomenon lead to a triggering of the overcurrent protective devices to protect the IGBTs (Insulated Gate Bipolar Transistor) of the VSC. Unbalanced voltage dips cause both current unbalance and current harmonics in the network, which may lead to turn on the operation of protective devices. Second harmonic ripple in a system may arise due to unbalanced fault causes a negative sequence component in the grid voltages. This ripple can be existing with DC link voltages and protection devices may be triggered if the maximum DC link voltage level exceeds. Additionally, this second harmonic current also causes poor power quality by producing non-sinusoidal current waveform at the converter of DG units.

Multiple technical solutions are developed to deal with above mentioned problem, such as phase locked loop (PLL) algorithms can deal with disturbances caused by second harmonic ripple [8].

4.4 Relay Type

Several types of relays are used in microgrid protection plans and they are voltage, over current, distance, admittance, differential and innovative relays.

4.4.1 Over current relay

Traditional over current relays are most suitable for conventional distribution networks. On the other hand, microgrid protection with traditional over current relays are very challenging and not suitable due to nature of short circuit level of fault current [39]. In grid connected mode, traditional over current relays can operate smoothly. However, once islanding occurs, short circuit level of fault current drops significantly due to disconnection of strong utility grid, may not have seen by the traditional over current relays. In this case, protection system designed for grid connected mode will not response and new protection techniques are required for safe islanding operation in microgrid. Thus, it is important to revise the settings of over current relays [35]. Accordingly, adaptive over current relays are designed in which settings of the relay are configured based on network situation and amount of short circuit fault current. It is also possible that different relay settings of the network can be stored, and the responsible relay of the faulted network may adopt proper setting based on network situation. This plan can be executed online or offline.

4.4.2 Distance relay

The intermittent nature of microgrid sources and the operation mode of microgrid unit causes variable fault current level and makes the over current relay protection complicated. So, the alternative of current magnitude based relays are developed due to above raised problem. Distance relay is a common alternative of over current relay which is unaffected by the small fault current existing in islanding mode of microgrids.

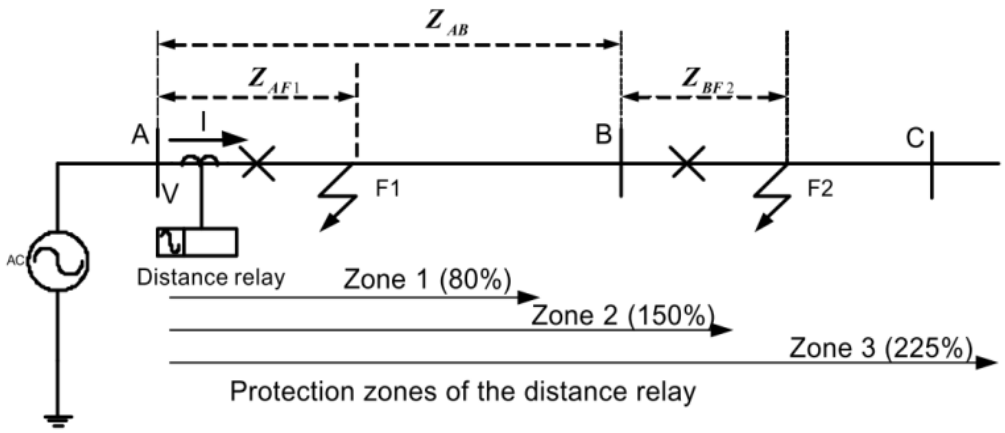

Figure 4.3: *Distance protection zone of distance relay [46].*

The distance relay calculates the impedance from the relay to the faulty point by comparing the fault current against the voltage at the relay location. Distance relay has three protection zones shown in figure 4.3. If a fault arises within distance relay operating zone, then distance relay acts to trigger the circuit breaker based on measured impedance. The impedance measured by the distance relay is a function of infeed currents causing relay to operate correctly.

4.4.3 Voltage relay

DG units output voltage are continuously monitored by voltage transformer (VT). Then d-q components of voltage are generated from three phase quantities. These values are compared with reference value and calculates the disturbance signal. The fault is detected according to the value of disturbance or error signal (V_{DIST}) (figure 4.4) [47]. The disturbance signal is the deviation of the measured voltage by VT from the given reference value. There is no deviation under normal operating condition which means V_{DIST} equal to zero. During faulted condition, V_{DIST} may vary according to the type of fault:

- Three phase fault – a DC voltage obtained as a V_{DIST}.
- Phase to phase fault – a DC voltage with AC ripple obtained as V_{DIST}.
- Single phase fault – the V_{DIST} oscillating between zero and a maximum value.

Still this scheme has limitation to deal with high impedance fault and intermittent nature of DG sources of microgrid.

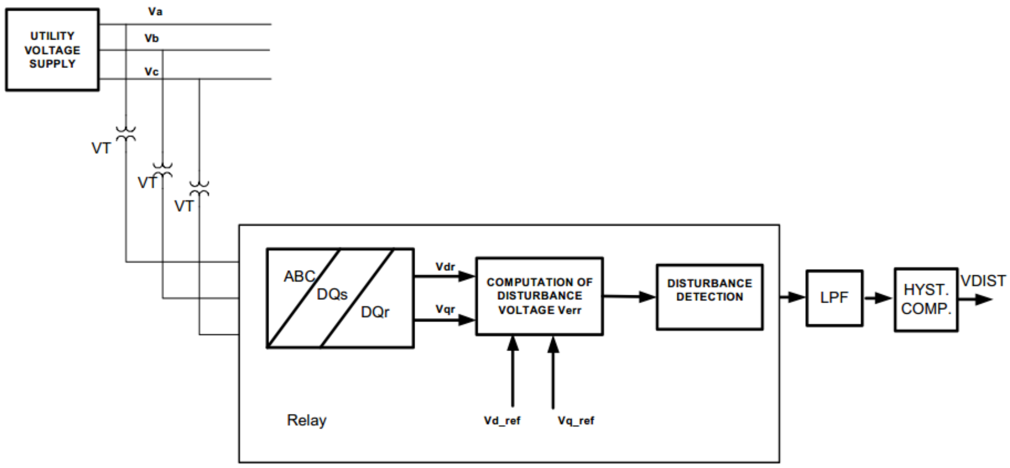

Figure 4.4: *Voltage relay in a network [47].*

4.4.4 Differential relay

Current entering and leaving in a feeder must be equal in normal operating condition. However, the current may not be same during a fault in a feeder. Therefore, differential relay based protection scheme is developed to detect and isolate the fault in a feeder. The current differential relay based protection scheme is not sensitive to intermittent nature of microgrid sources, bi-directional power flow and number of DG points.

So that it provides protection for both island and grid connected modes of operation.

The authors of [48] proposed a protective plan in which each differential relay has five elements to provide feeder protection. Three phase elements are for three phase networks and other two elements represents zero and negative sequence currents. Figure 4.5 shows the differential relay based feeder (left) and bus protection for microgrid (right). The differential relay based protection is uneconomical due to structure and component required.

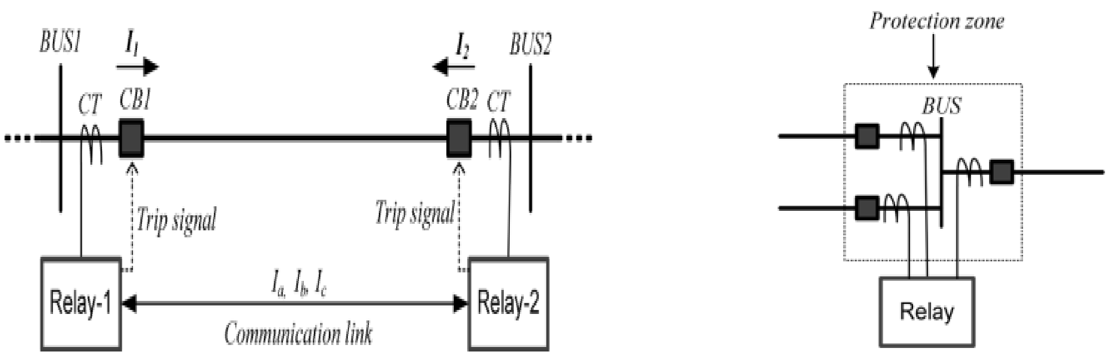

Figure 4.5: *Differential relay based feeder (left) and bus protection for microgrid (right) [48].*

4.4.5 Proposed new relay technology

Admittance relay mainly measures the line impedance to calculate the tripping time. According to reference [49], the normalized admittance of the feeder is used to obtain an inverse time characteristic (tripping time) of the relay. Figure 4.6 shows the relay tripping characteristics based on line admittance. The tripping will be faster for higher value of line admittance. The fault nearest to relay location will be cleared very quickly [49].

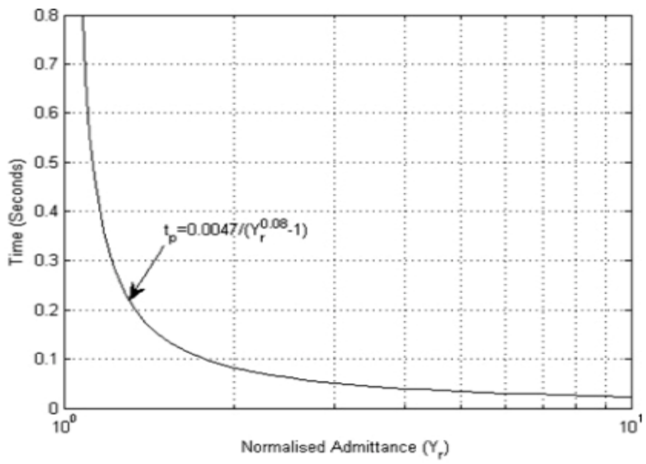

Figure 4.6: *Admittance relay tripping curve [49].*

The tripping time will be higher for long microgrid feeder. So, it should be taken account when a microgrid protection system is designed with admittance relay. The admittance relay based system may also show slow tripping for high impedance fault, harmonics measurements error and DC component decaying.

Innovative relays are modern microprocessor based relays. Reference [50] suggest a relay which can protect the microgrid in island mode and normal mode can be protected by the mechanism of [51]. Innovative relay detects fault based on the symmetrical components of the microgrid. The relay works with negative sequence component of current to detect asymmetrical faults and identify the fault location based on both current and voltage [51].

4.5 Fault Type

Two types of short circuit faults occur in power system network. These are symmetrical faults and unsymmetrical faults. Symmetrical fault includes three phase fault and three phase to ground fault. Single line to ground fault, line to line fault and Double line to ground faults are categorizes as unsymmetrical fault.

Generally, microgrid protection plans are designed by considering three types of faults found in the different literature studies. Those are high impedance fault (HIF), low impedance fault (LIF) and faults due to oscillation of network voltage.

Low impedance faults in a network have higher short circuit fault current which can easily be detected by traditional protective devices described above. A high impedance fault is always a great concern for network operators for safety reason as its very difficult to detect. High impedance fault has very low fault current in nature due to high impedance and makes the situation challenging for traditional protective devices to sense and trip. That is even difficult for ground fault relays when there are multiple grounded paths and return current takes different paths [40].

HIF has been investigated by many scholars in past years due to its nature of difficulty. The researchers finally end up with some special protective scheme such as adaptive over current protection, differential protection scheme of microgrid etc. Reference [12] suggest an innovative relay scheme which contain modules having three parts for protecting microgrid network in the islanded mode, normal mode and in case of high impedance faults.

Another type of microgrid fault protection scheme is developed by considering fault caused by voltage sag in a network. According to researchers, a large potential difference appears across the distribution feeder and the DG inverters during the voltage sag period. In these circumstances, high currents can flow through the paths having small impedance. This will cause to damage low power devices such as inverter components and also microgrid parts if the protective devices does not work and are unable to clear the voltage sag.

4.6 Communication Type

Communication play a key role on microgrid fault protection. The process of gathering information and communicative infrastructures are divided into three categories in a microgrid fault protection network. Those categories are: local information based, wide area measurement (WAM) and hybrid scheme.

4.6.1 Local information based

A local fault detection method based on local variables such as current and voltage value where a DG source is connected. This protection plan is almost like the traditional protection plans. In this scheme, only the local information of the relay and DG unit are collected and analyzed for further investigation. The local information based protection plan is very secured as the information of all nodes of the network are not accessible. One more advantage is that the plan has low application cost because of minimum change required to the fault protection system. Although this approach has several disadvantages such as due to all decisions are made locally makes the plan unable to take the best decision which cannot employed globally [40].

4.6.2 Wide area measurement (WAM)

A bigger system need more sophisticated protective system. Normally, complex system employs communication channels for data collection that allows a time scale of few seconds for required operations [40]. A protection system depends on wide area measurement (WAM) have following units: a supervisory remote-control unit (SRCU), secure and high speed communicative base, wide area measuring units, and digital protective devices which are configurable. The operation of this scheme carried out based on the combination of above units. The SRCU is mainly responsible for receiving data from all over the networks and then performs required calculations and decides whether a fault occurred or not. If a fault is found, then SRCU sends the necessary commands to protective devices which are nearest to fault location. The latest communication protocol such as IEC 61850 is used between protective devices (IED, measuring devices) and control center [40]. This protocol contains set of rules and is a standard for substation automation.

4.6.3 Hybrid scheme

Hybrid scheme is mainly a mixture of above two communication infrastructures. In this scheme, SRCU works as a highest layer and a local layer is also introduced. Normally decisions are taken by local layer and if any data is inaccessible by local layer then highest layer are called to take over the faulted situation and handled [40]. The scheme has several advantages including faster operation and simple communicative architecture.

5. Different methods of microgrid protection

Islanding detection is one of the critical issue to design an effective protection system. That's why microgrid protection is analyzed by considering two aspects: islanding detection and fault current protection in grid connected and islanded mode. A feasible protection technique has to be implemented for the microgrid in a manner that maximum portion of the network can be served during any type of fault by isolating the faulty part of the network. It means that an effective protection scheme should design with capability of minimum outage and maximum reliability. Protection systems are designed in two layers: primary protection system and backup protection system. Primary protective devices act in case of any short circuit fault within its coverage area. However, backup protective devices provide support in the failure of primary protection scheme. A very simple protection is employed using overcurrent relay and fuses in traditional radial feeder network. But the integration of DGs with traditional power system network makes the overall network complicated in every aspects as discussed in previous sections. This integration has brought a lot of changes specially in short circuit fault current depending on DG type, number of DGs employed and microgrid mode of operation. Hence, it is excessively challenging to design a proper protection scheme to meet above issues. The next sections are about islanding detection and techniques for protecting microgrid in both operating mode.

5.1 Islanding detection methods of microgrid

Islanding is a circumstance that happens when a segment of network is isolated from main power grid, but the small part still fed by one or more DG units. The distribution network has no electricity in case of fault in traditional transmission network. However, this prediction is not true anymore due to the integration of DG units in distribution network. There are a lot of research work have been done on island detection techniques under two sub-headings: local methods and remote controlled. Passive, active and hybrid methods are part of local technique.

Passive detection techniques monitor few variables such as frequency, voltage, rate of change of frequency (ROCOF), rate of change of frequency over power (ROCOFOP), rate of change of power signal, total harmonic distortion (THD), phase jump detection (PJD) [35]. The value of above parameters compared against a set of pre-defined value and thus islanding is detected. Passive detection techniques operate very fast to detect islanding without hampering network normal operation. However, mismatch of the values is so small that they are not trustworthy. The principal limitations of passive detection methods are large non-detection zone (NDZ) and define the threshold value of examined parameters [35].

Active detection methods are active frequency drift (AFD), frequency jump (FJ), active frequency drift with positive feedback (AFDPF), sandia frequency shift (SFS), sandia voltage shift (SVS), negative sequence current injection, impedance measurement (IM). Active detection methods are intentionally injected perturbations to detect the response of system voltage, frequency, impedance and power. Islanding is detected based on their responses. This method improves the drawbacks of previous methods described above in a wat that it is applicable for smaller non-detection zone and even if the mismatch of power is very less. However, they have some disadvantages such as more islanding detection time required compared to passive methods and power quality degradation due to injected disturbance.

Active and passive methods are applied together in hybrid islanding detection method. At first, passive methods are used to continuously monitor the network for island suspicion and then perturbation added to system parameters for further confirmation. Hence, the major drawback of hybrid detection method is, it takes long time due to passive and active method involvement.

Remote methods are developed using communication link between main grid and microgrid to minimize the problems brought by passive and active islanding detection methods. These method monitors circuit breakers immediately to detect islanding and implement feasible protection plan. Some of the remote-control islanding detection methods are [52]: supervisory control and data acquisition (SCADA), power line carrier (PLC), intertripping /disconnection signal. These methods operate very fast and even they have no non-detection zone which provides very high-power quality. Remote methods are well reliable for multiple inverter connected DG systems. But the problem is that implementation cost is high so that they are not good choice for small systems.

5.2 Replacement of protective devices or settings

The introduction of DG units in distribution network arises many problems related to protection such as selectivity of protective devices or their settings. In this method, protective devices and their operating values are replaced to accomplish intended protection in faulted locations where conventional protection scheme has faced disruption. It was already established by researchers that directional over current relays (OCR) are required instead of non-directional OCR [14-31]. The main problem of non-directional OCR is that they do not provide expected sensitivity and security during power flowing in both direction of feeder caused by DG sources.

A fault protection method using this technique was proposed in [53]. The authors restrain fuse damage in a DG installed network during a temporary short circuit fault. In this method, a fuse must have to be replaced by recloser (R_{LAT}) in a branch that contained DG unit. In addition to this change, a relay (R_{DG}) has to be placed near to the connection point of DG unit. The testing network used for this method is shown in figure 5.1 [53]. The recloser placed near bus-2 is mainly responsible to isolate the feeder main power line during a fault. The fault occurred near bus-6 was further fed by installed DG unit. To prevent fuse2 meltdown at faulted network, R_{LAT} isolate the DG network in fast mode to stop flowing of fault current fed by DG unit.

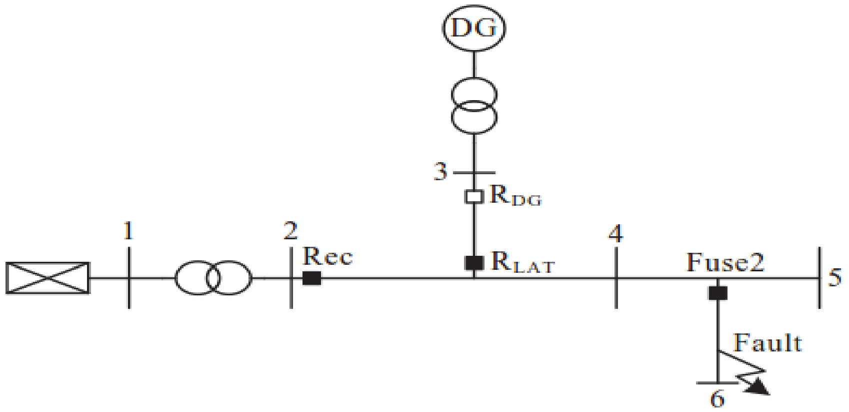

Figure 5.1: *A radial feeder including DG unit with protective devices [53].*

This method is impractical due to the dynamic nature of DG unit in microgrid network. Different types of microgrid topology also affect this protection plan and it is also difficult to change protective devices based on the change of topology and network size.

5.3 DG unit disconnection during a fault

In this method, the current section unit (CSU) of protection system takes quick action during fault to isolate DG unit from rest of the distribution network. A fast switch is used for the disconnection of DG unit. CSU is mainly placed at the point where DG unit has been installed which always monitor the current level for the detection of fault. After the disconnection of DG unit, the network operates normally without DG unit by activating the settings of protective devices installed at pre-DG state. This procedure of DG disconnection is one of the easiest technique to handle the problems caused by the addition of DG unit in the network. The benefits are noted according to the author of [54]:

- Low cost and less complex protection plan.
- Replacement of protective devices or settings are not required.
- DG unit reconnected through synchronism to the main network.

A faster operation of DG unit disconnection is required to utilize the above advantages and power electronics switches have to be used instead of circuit breakers (CB) to perform the operation in time [54]. During the reconnection process of DG unit to the network, a transient condition may arise which further leads to a fault sense by CSU. Hence, [54] proposes a solution that CSU have to wait at least seven cycles to detect the fault.

Finally, DG unit disconnection is not the solution during all type of fault. The main purpose of DG unit installation to the network is violated if it gets disconnected during faulted condition. In addition to this, it also violates the purpose of microgrid in islanded mode. Therefore, this protection strategy have contradiction with the purpose of microgrid in islanded mode.

5.4 Fault current limiters (FCL) in microgrids

The main purpose of using fault current limiter in a network to reduce fault current level without complete network disruption during a fault. Hence, protective devices can operate with their predefined overcurrent settings due to current limiting caused by FCL. The efficient way to minimize the negative impacts of DG units is keeping down the short circuit fault current level on distribution networks protection. This is achieved by using fault current limiter (FCL). Basically, FCLs are series impedance that can added with DG units and lines. The fault current fed from utility grid to microgrid are controlled by insert an FCL at point of common coupling (PCC) and with DG unit in series. In normal operation, there is no significance of FCL and it provides zero impedance to the network. During faulted condition, the value of impedance increases rapidly so that value of short circuit current in tolerance level. To prevent losses and voltage sag, it should be kept in minimum position (zero impedance) and on the other hand, it should operate in maximum position in short circuit conditions. Figure 5.2 illustrates the fault current limiting phenomena in general.

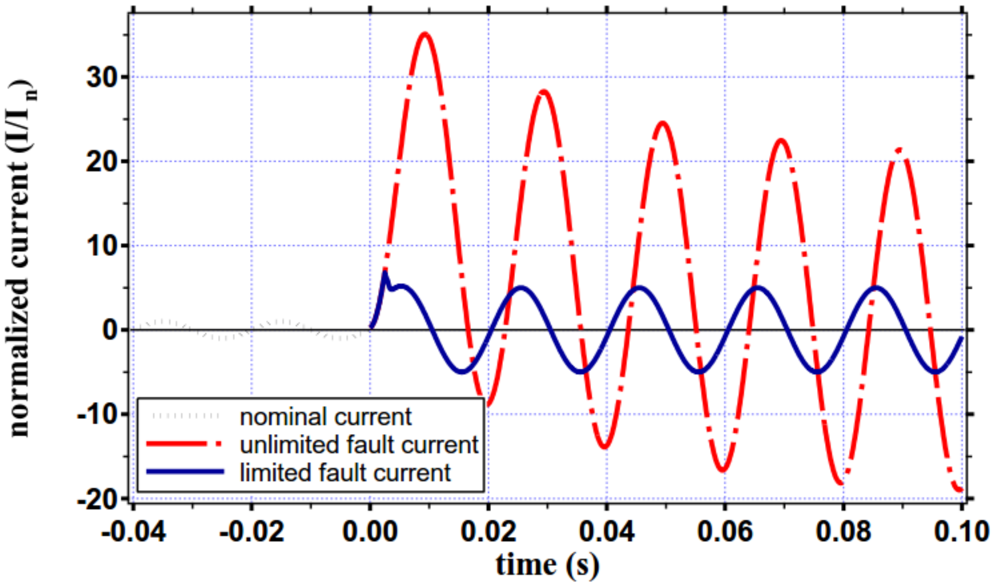

Figure 5.2: *Impact of FCL in fault current level [55].*

In [56], the main focus of authors is to find out the optimum location for FCL in a distribution network. FCL are placed in different location and observed the short circuit fault current level. It is suggested that a DG unit and FCL have to placed in same branch to get the maximum benefits such as reduced the over current relays operation time.

There are three types of fault current limiters available to limit the short circuit level. These are superconducting FCL (SCFCL), solid state FCL (SSFCL), and electromagnetic FCL (EMFCL). The non-linear behavior of superconducting materials with current, temperature and magnetic fields. The current limiting by SCFCL is mainly based on these non-linear responses. Hence, current limiting is done under faulted situation if the threshold value of these parameters exceeds. The predefined values of these variables are within limit under normal operating condition, hence, the current flowing through protective devices. In case of SSFCL, the current controlling mechanism operates based on the switching (off/on) of semiconductor devices. The measured magnetic field is used for current limiting purpose in electro magnetic fault current limiter.

A solid state FCL was proposed in [57], having a current limiting element, voltage limiting element, fast solid-state switch and mechanical series switch. Due to the presence of solid state devices, it causes noticeable switching loss. Mechanical switches and breakers are used in this type of FCL and needs more time to operate and unable to bypass fault current across their terminals or contacts. To overcome this weakness, a new technique was proposed in [58] known as hybrid fault current limiter. This is one of the feasible scheme proposed which is an amalgamation of electromagnetic FCL, solid state FCL and super conducting FCL shown in figure 5.3. The circuit diagram of hybrid FCL shown in figure 5.3 has three parallel paths. A fast mechanical switch, semiconductor devices and resistor are in path A, B, C respectively. Fault current completion in a way that path A commutates the current on to path B and path B forces the current in path C.

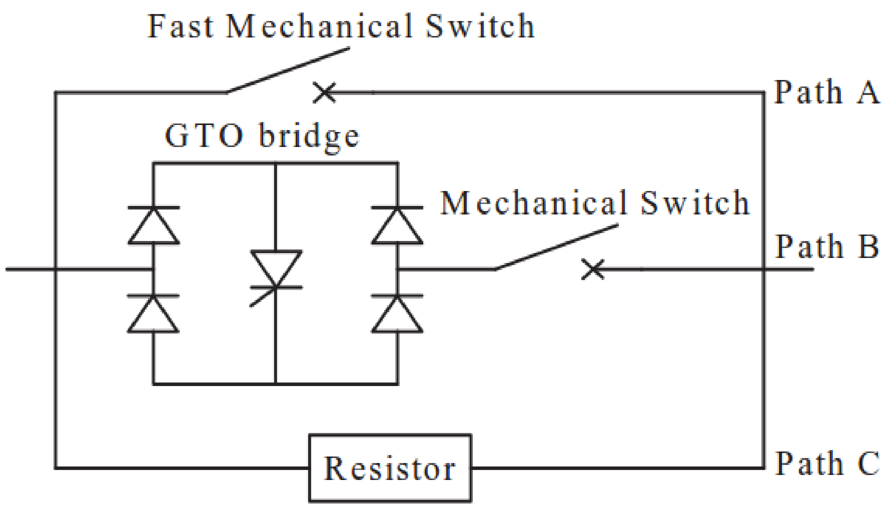

Figure 5.3: *Hybrid FCL for single phase [58].*

5.4.1 I_S limiter

I_S limiter is considered a fault current limiting device. This device is a combination of current limiting fuse and fast switch connected in parallel. This equipment provides economic and reliable operation against large current. Under no fault condition, current pass through the low impedance fast switch. A control circuit is used to detect the fault and sends tripping command to fast switch so that fault current can flow through fuse which has high breaking capacity. Fuse and switches must be replaced after every operation as I_S limiter is a one-time device. Current limiting effect of I_S limiter has shown in figure 5.4.

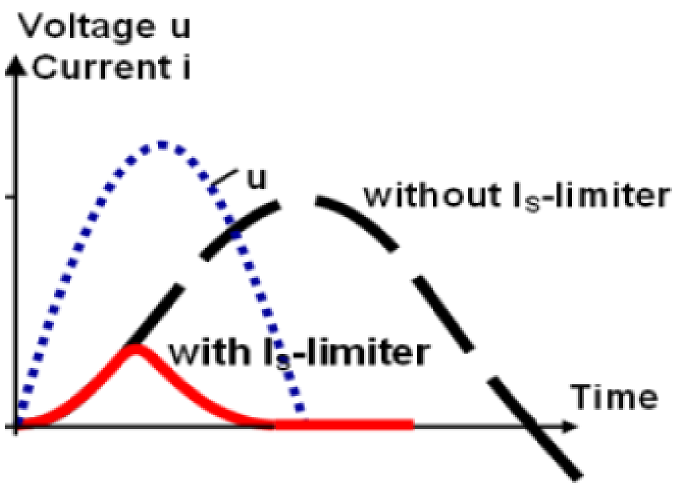

Figure 5.4: *Current limiting effect of I_S limiter [55].*

5.5 Adaptive protection for microgrid

The presence of DG units throughout the distribution network changes the fault level and strength of fault current. Hence, the reconfiguration of protective devices in terms of power rating is required. This section presents an adaptive protection plan that can efficiently response towards the changes brought by the implementation of DG units in microgrid network. The definition of an adaptive protection according to [59] is as follows: "an online activity that modifies the preferred protective response to a change in system requirements or conditions". The following technical requirements are needed for real application of adaptive protection system in microgrid network [55]:

- Implementation of digital and directional over current relays instead of traditional solid-state and electro-mechanical relays or fuses which do no have any selectivity feature and directional element.
- The digital microprocessor-based relays must have different settings, especially for different fault current characteristics and their settings can be changed from remote location or locally.
- The communication infrastructure between relays and microgrid controller has fast data transmission rate with high security. A standard protocol such as IEC-61850 should be used for proper communication to ensure a task completed successfully.

Figure 5.5 illustrates a communication assisted microgrid central controller (MCC) based MV/LV microgrid network including primary switching devices. The assignments of MCC is done by a control station computer or a person-controlled PC and a programmable logic controller (PLC). The blue lines in figure 5.5 shows the communication link between microgrid components with MCC. The protocol used in this communication is IEC-61850. Digital directional relays can communicate with MCC through this link and MCC also able to updates their settings shown in figure 5.5.

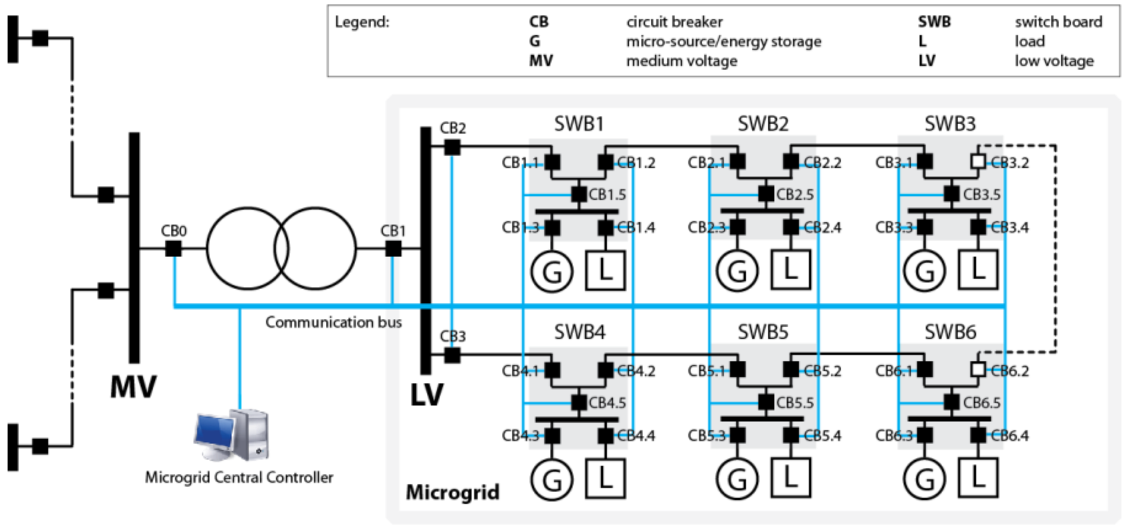

Figure 5.5: *MV/LV microgrid with centralized adaptive protection scheme [55].*

During a fault, the individual digital directional relays sense the fault direction and magnitude, thus can take tripping decision by own (locally) without waiting for MCC operation as shown in figure 5.6. A CB is opened in case of tripping condition met, otherwise if there is any abnormal condition arise, then MCC checks and update new tripping conditions to digital directional relays. In this case, MCC performs operation by measuring current in specific direction and further it is compared with actual relay settings.

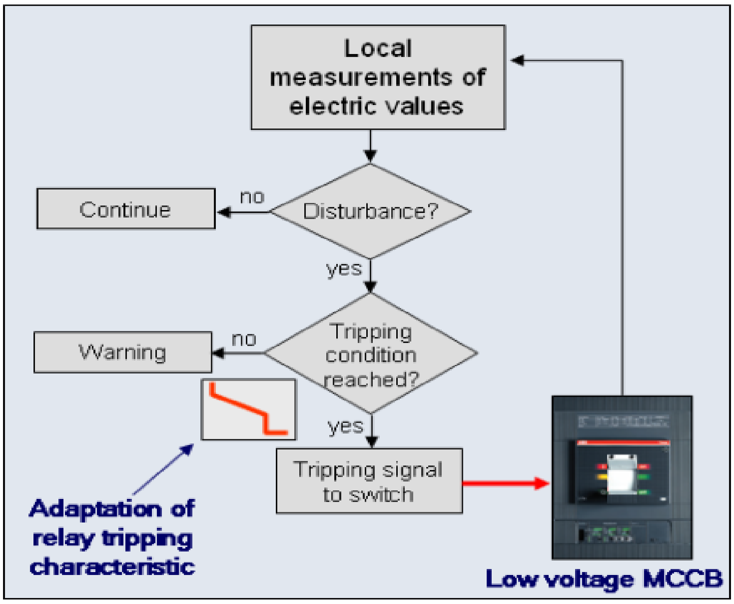

Figure 5.6: *Protection stages inside of digital IEDs [55].*

The main purpose of adaptive protection scheme is to monitor the microgrid network all the time and run it with updated latest settings. This aim is accomplished through a special module inside MCC which monitors the microgrid network periodically and replace the old settings with latest settings. This monitoring and updates can be done in two ways, either offline or online. The next subsections 5.51 and 5.5.2, focus on the issue related to adaptability.

5.5.1 Off-line adaptive protection

In off-line adaptive protection, microgrid central controller (MCC) construct event table, which means that set of possible meaningful configuration with DG units is formed for off-line fault analysis. The number of element for each record in event table is equal to number of circuit breakers (CB) connected to the microgrid network. Some CBs have high priority than other CBs, for example the CB connecting MV and LV grids. The event table is binary encoded (for example, CB is close means 1 and CB is open means 0) shown in figure 5.7. Then, different faults are applied in all possible location in microgrid network for each configuration of event table and then fault current pass through each relay is recorded in another structure called fault current table. The microgrid topology and DG unit status (on/off) are also changed during this process. Finally, the directional overcurrent relay settings with time delay are calculated based on these results and stored in another structure called action table. Action table and event table has same dimension. The flow chart in figure 5.8 (a) shows the steps of off-line adaptive protection scheme.

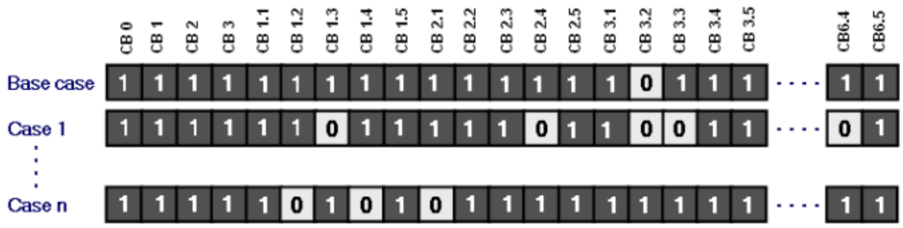

Figure 5.7: *Event table structure for the network shown in figure 5.5 [55].*

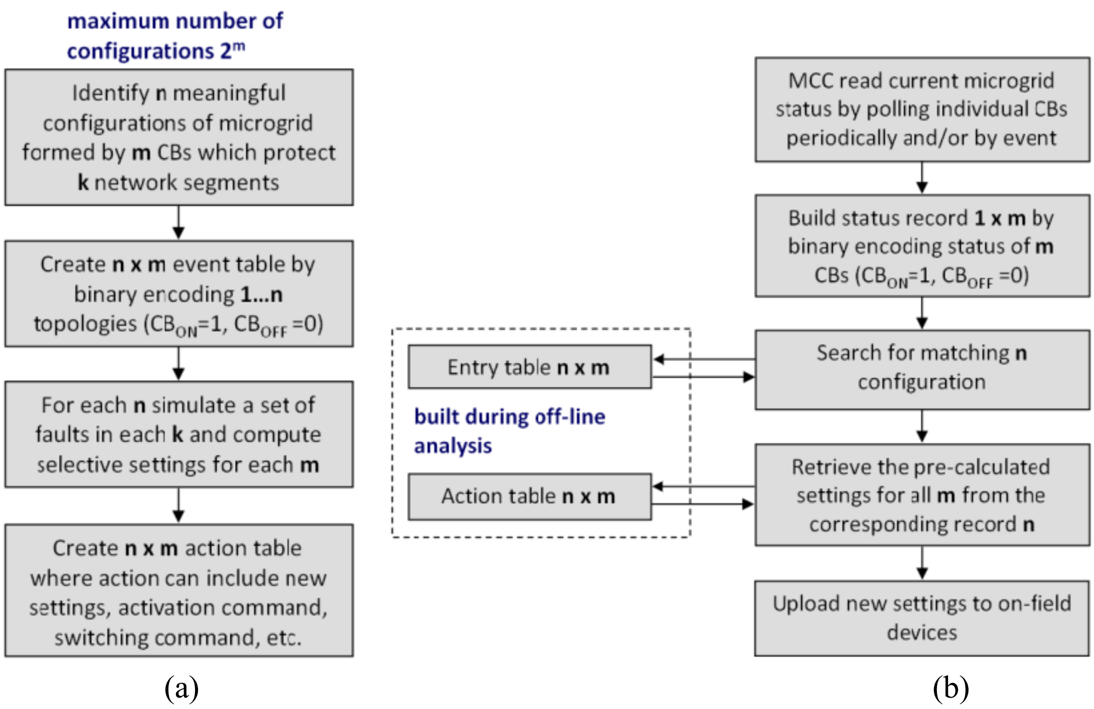

Figure 5.8: *(a) Phases of adaptive protection in off-line (b) Phases of adaptive protection in on-line [55].*

5.5.2 On-line or real-time adaptive protection

In on-line adaptive protection, the microgrid central controller always monitor the microgrid network including DG units, loads and protective devices. This monitoring is done either periodically or triggered by an event such as protection alarm, tripping of CB etc. The present status of microgrid network is received by MCC and form a status record which has an analogous structure as a single record in the event table. Then the status record is used to compare with predefined event table which is constructed in off-line. Finally, MCC updates the settings of protective devices after retrieving predefined value from action table for any specific status record via the communication link. Figure 5.8 (b) illustrates the sequence of on-line adaptive protection scheme.

6. Case study: IIT microgrid

A literature based case study is presented in this chapter to show the performance of adaptive protection strategy implemented in grid connected and islanded mode operated microgrid network. Illinois Institute of Technology (IIT) has their own underground distribution network. This campus distribution network have microgrid network with a rating of 4.16 kV. The topology of the microgrid is shown in figure 6.1. The south substation (SS) and north substation (NS) are coupled together through a cable to increase the network reliability in case of any utility feeder failure connected to the substations. In addition to this the microgrid network has phasor measurement units and high reliability distribution system (HRDS) for smoother and seamless operation of campus distribution network. The IIT microgrid includes seven distribution loop structure with different DG units such as solar panel, wind power plant, gas turbine and battery storage devices. Buildings and charging stations are used as microgrid load. HRDS vista switches are used to integrate the components in IIT microgrid network. The IIT microgrid loads are controllable and buildings have automation technologies for demand response and thus enhance energy efficiency.

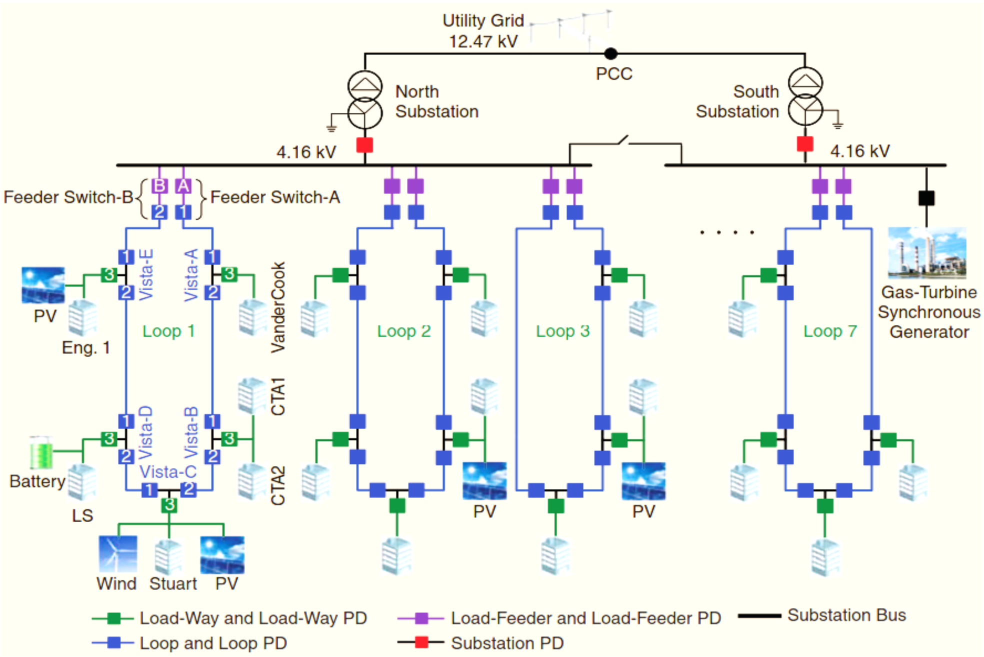

Figure 6.1: *Microgrid protection system architecture of IIT [41].*

Vista-A, Vista-B, Vista-C, Vista-D, and Vista-E are three port switches in loop1-7 indicated in figure 6.1. Two ports of switches for example, E-1 and E-2 are assigned for loop protection having protective devices (PD) and third port is for load PDs (E-3) which support the DG unit or controllable loads in distribution network. The substation transformer rating is 12.47/4.16 kV with delta-wye connection and protective devices (PD). The south substation has gas turbine synchronous generator (SG) connected through generator PDs, and cross tie cable is used in between two substations for connection establishment.

6.1 Adaptive Protection methods in the IIT Microgrid

The significant difference between short circuit levels in island and grid connected mode has forced to implement adaptive protection in microgrid. The relay settings for grid connected mode and islanded mode are different in adaptive protection scheme. The proper settings chosen by responsible relay based on microgrid mode of operation.
Figure 6.2 illustrates the hierarchical layout of IIT Microgrid protection system. The hierarchical structure includes four coordinated protection levels, seven loops with localized differential protection, and directional overcurrent relay in load way. These are implemented by communication assisted HRDS switches and digital directional relays. The fundamental properties of the IIT microgrid to achieve desire protection are as follows [41]:

- Balancing of DG technologies to increase the short circuit fault current level in islanded mode. Synchronous generator is used in IIT microgrid to balance the fault current during islanded mode thus over current relay can operate effectively.
- The IIT microgrid protection principle is based on localized differential protection and a communication supported directional overcurrent relays.
- The IIT microgrid has adaptive relay settings for islanded and grid connected mode. As fault current in IIT microgrid reduced in islanded mode shown in table 6.1, the overcurrent relay waits for further instruction from microgrid controller to change their settings.
- Loop structure mainly increase the network reliability and facilitate hierarchical protection at IIT microgrid.

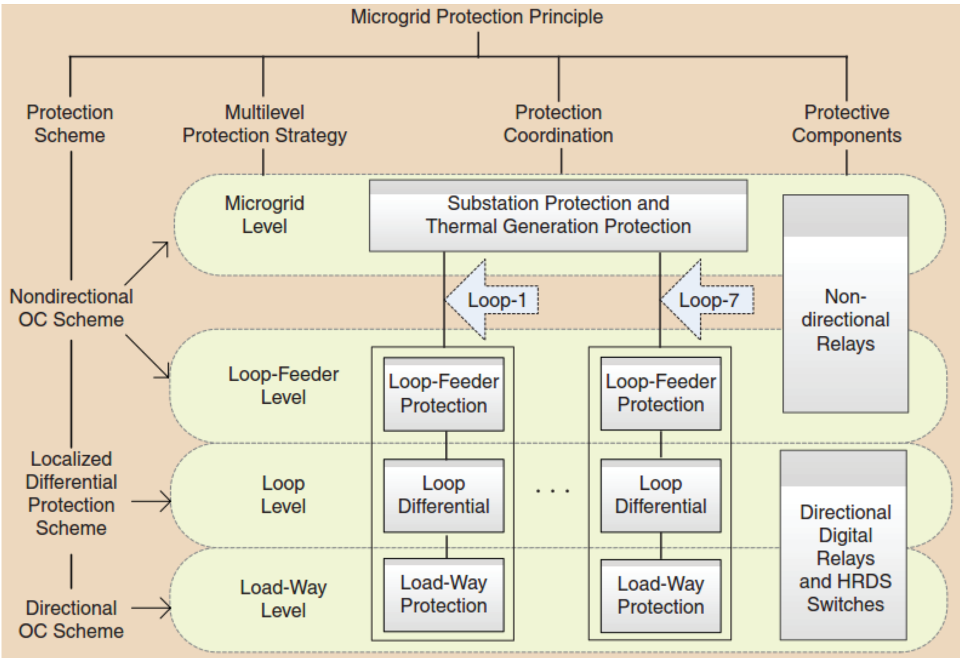

Figure 6.2: *Hierarchical layout of IIT Microgrid protection system [41].*

The protection strategy at IIT microgrid is classified into four layers [41]: load level, loop level, loop-feeder level and entire microgrid level. These hierarchical protection scheme covers both primary and backup protection in IIT microgrid network. For example, in case of load PD failure, loop level PDs provide additional backup protection.

Fault Location	Islanded Mode	Grid-Connected Mode	
		PCC at NS	PCC at SS
Loops 1–3	3 kA[a] ~ 4 kA[b]	12 kA[a] ~ 15 kA[b]	8 kA[a] ~ 9 kA[b]
Loops 4–7		8 kA[a]~ 9 kA[b]	12 kA[a]~ 15 kA[b]

[a]Fault current is lower when the fault is close to the middle point of the loop.
[b]Fault current is higher when the fault is close to the loop feeder. (All currents are calculated for single-phase to ground fault.)

Table 6.1: *Fault current magnitude at IIT microgrid [41].*

In loop-1, a single phase to ground fault is applied in modeled IIT microgrid shown in figure 6.1. Low impedance faults are simulated. The following cases are simulated to justify the compatibility of adaptive protection scheme in IIT microgrid network.
Case A: Grid connected mode protection – fault in load section.
Case B: Islanded mode protection – fault in load section.

Case A: Grid connected mode protection – fault in load section.

In this case, it is proved that how protection system at IIT microgrid clear a grid connected fault. The microgrid is connected to main grid through north substation and the synchronous generator are disconnected through command issued by microgrid controller. At t=1 sec, a single-phase ground fault applied at vista-c load part in loop-1 (figure 6.1). The simulation results for grid connected microgrid fault is shown in figure 6.3 (a). It can be seen from the figure 6.3 (a) that fault is quickly cleared by load protective device (C3) and fault current is approximately 13kA which is mainly contributed by utility grid.

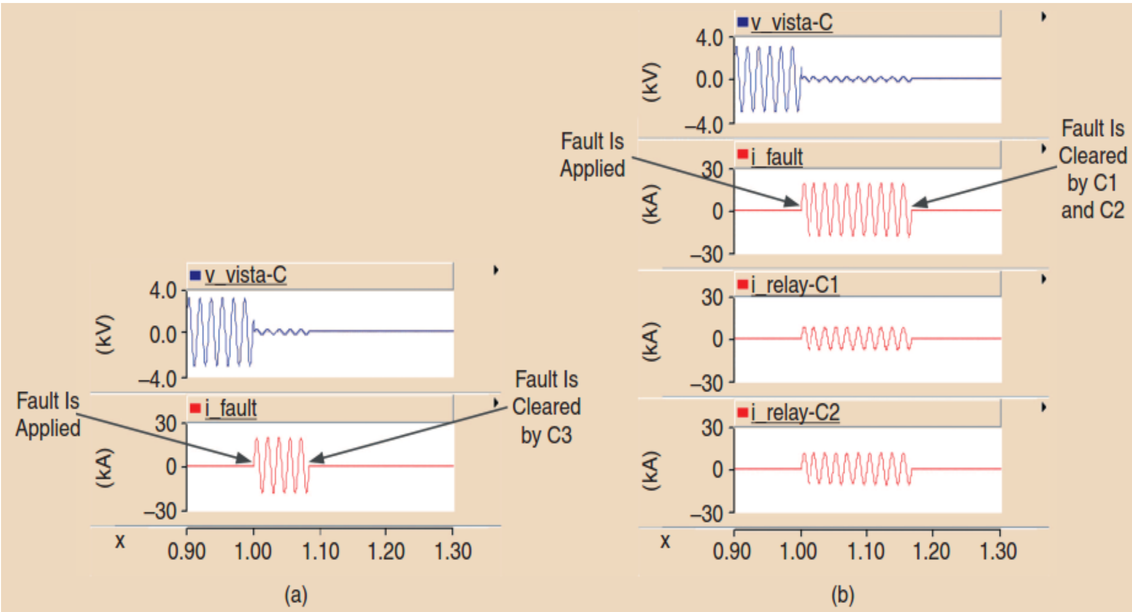

Figure 6.3: *SG disconnected (a) fault is cleared by load PD-C3 (b) fault is cleared by backup protection PDs, C1 and C2 [41].*

One more thing has been simulated in this case that if main protection relay fails to operate how back up protection will provide support. Here, it is assumed that load PD (C3) is failed and protection is provided by loop PDs (C1 and C2). This is shown in figure 6.3 (b) with fault current seen by relays. It is noticed that the fault clearing time in later case is little bit higher than previous one as backup protection is responsible for fault clearing.
Figure 6.4 depicts the simulation results for the similar fault has applied at t=3sec. In this case synchronous generator is connected and it supplies 4 MW to microgrid network. The results show that fault current is higher compared to previous case as synchronous generator also contribute to fault current. In this case, SG contribute approximately 3 kA (i_gen) and utility grid provide 12 kA (i_grid) to the fault current. Figure 6.4 (a) and figure 6.4 (b) indicates the scenario for primary and backup protection scheme respectively.

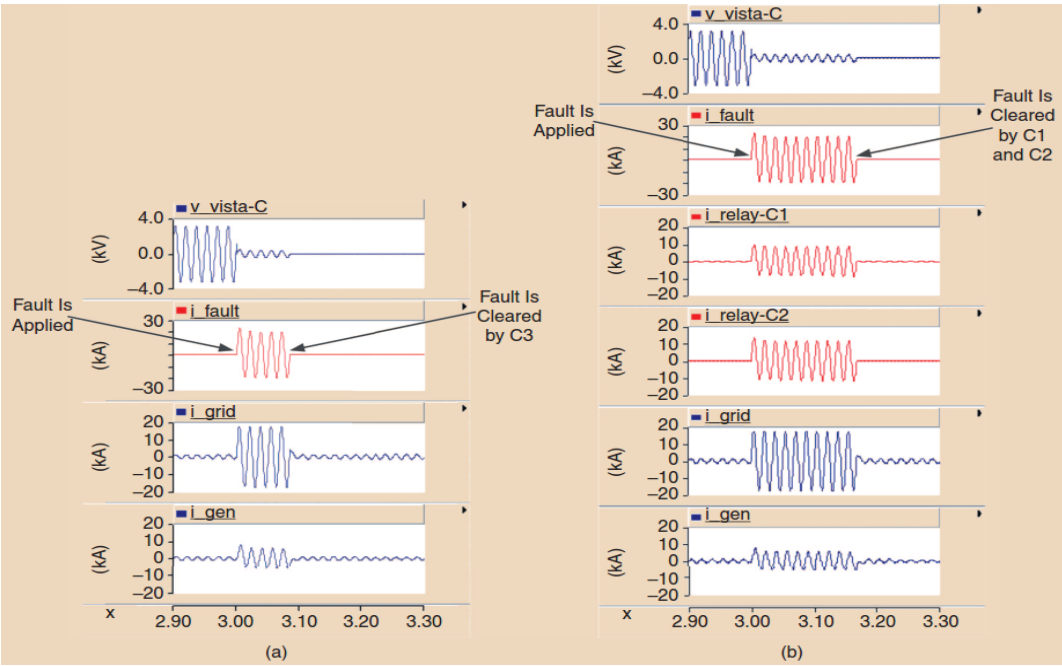

Figure 6.4: *SG connected with P_{SG}=4MW (a) fault is cleared by load PD-C3 (b) fault is cleared by backup protection PDs, C1 and C2 [41].*

Case B: Islanded mode protection – fault in load section.

In islanded mode operation at IIT microgrid, the central microgrid controller instruct load PD and loop PD to change their relay settings as fault current level in islanded mode has changed significantly. A single phase to ground fault has occurred at t=3sec and synchronous generator is mainly fed the microgrid network. The fault current supplied by SG is about 3.2 kA (i_gen) shown in figure 6.5. The fault is cleared by load PD as shown in figure 6.5 (a). Further in case of load PD failure, the backup loop relays cleared the fault as shown in figure 6.5 (b). The clearing time is higher as it includes both primary and backup protections. The fault current is significantly reduced in this case compared to grid connected mode case described above.

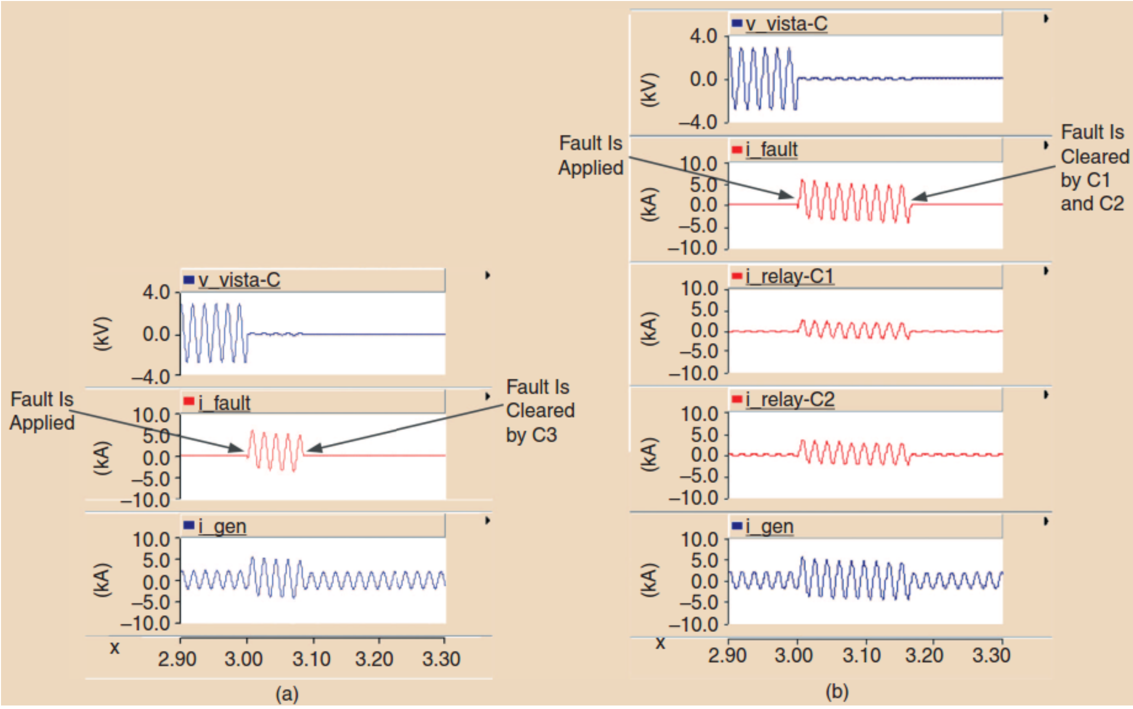

Figure 6.5: *Islanded mode protection (a) fault is cleared by load PD-C3 (b) fault is cleared by backup protection PDs, C1 and C2 [41].*

7. Conclusion and Recommendations for future work

This chapter provides an idea of entire thesis work with future recommendations that are required while planning protection strategy for the microgrid based on various key factors identified.

The main target of the thesis is to solve the protection problem caused by DG integrated microgrid network. In this regard, this research focus on existing different studies and analyzing them for identification of an effective protection scheme. It is found from thesis research that short circuit fault current level changed due to the existence of DG unit and the operating mode of the microgrid either in grid connected or islanded mode. It is also noticed from literature study that penetration of DG unit into microgrid network causes some phenomena such as prohibition of automatic reclosing, sympathetic tripping, and blindness of protection. The research is looking for to find out important parameters that can influence the microgrid protection system. Several key factors are found from literature study that includes microgrid topology and type, DG unit type, relay type, fault type, communication methods. The findings need to be addressed that the mesh configuration of microgrid needs more sophisticated protection scheme compared to radial and ring architecture. The factor DG unit type indicates that a synchronous generator have more contribution to fault current compared to inverter interfaced DG units. Communication among protective devices with substation also play a significant role for safe and faster operation of microgrid. The impact of relay type includes their settings with tripping characteristics.

However, various microgrid protection strategies were reviewed from different studies already proposed. Replacement of protective devices and disconnection of DG unit during fault are of them. It is impractical every time to change the protective devices during fault and the disconnection of DG unit violates the principle of microgrid as microgrid introduce to the distribution network increased reliability. The protection based on fault current limiter provides satisfactory solution, but the cost of implementation is higher. The advantage of using fault current limiter is that it limits the fault current contribution from grid to microgrid in acceptable level. But it is still challenging for FCL based protection solution due to the fact that DG connected network is very dynamic in nature. Hence, adaptive protection scheme is studied further. It is found that adaptive protection can apply in both offline or online. But the problem with offline adaptive protection scheme is that it cannot incorporate all the changes based on identified factors discussed above. The online adaptive protection strategy provides reliable and secured microgrid protection based on any changes occur within the network. A communication link is required for successful operation of adaptive protection scheme. The performance of adaptive protection strategy is presented through a literature case study of IIT microgrid network in USA.

However, there is some uncertainties in adaptive protection scheme in the case of communication failure and availability of digital protective device. The infrastructure cost is also higher which needs to be considered before implementation. That’s why in the future, there is chance to work with alternatives of adaptive protection plan.

References

[1] Lin X, Zhang R, Tong N, Li X, Li M, Yang D. Regional protection scheme designed for low-voltage micro-grids. Int J Electr Power Energy Syst 2015; 64:526–35.

[2] Mathur A, Das B, Pant V. Fault analysis of unbalanced radial and meshed distribution system with inverter based distributed generation. Int J Electr Power Energy Syst 2017;8 5:164–77.

[3] Bayat A, Bagheri A, Noroozian R. Optimal siting and sizing of distributed generation accompanied by reconfiguration of distribution networks for maximum loss reduction by using a new UVDA-based heuristic method. Int J Electr Power Energy Syst 2016; 77:360–71.

[4] Ma J, Wang X, Zhang Y, Yang Q, Phadke AG. A novel adaptive current protection scheme for distribution systems with distributed generation. Int J Electr Power Energy Syst 2012; 43:1460–6.

[5] Tan X, Li Q, Wang H. Advances and trends of energy storage technology in microgrid. Int J Electr Power Energy Syst 2013; 44:179–91.

[6] R. Lasseter. "MicroGrids". In: IEEE Power Engineering Society Winter Meeting. Vol. 1. 2002, pp. 305-308.

[7] SmartGrids, European Technology Platfrom. Vision and Strategy for Europe's Electricity Networks of the Future. 2006. url: http://ec.europa. eu/research/energy/pdf/smartgrids_en.pdf (visited on 12/09/2015).

[8] H. Laaksonen. "Technical Solutions for Low-Voltage Microgrid Concept". Acta Wasaensia 241. Dissertation. University of Vaasa, Apr. 2011. 271 pp.

[9] M. Soshinskaya et al. "Microgrids: Experiences, barriers and success factors". In: Renewable and Sustainable Energy Reviews 40 (Dec. 2014), pp. 659-672.

[10] Sampo Turunen. Protection of microgrids and distributed energy resources based on IEC 61850. Master of Science thesis submitted in Tampere University of Technology, 2016.

[11] Brearley, Belwin J. / Prabu, R. Raja, A review on issues and approaches for microgrid protection. Renewable & sustainable energy reviews; 67 (2017); 988-997.

[12] Mohammad Amin Zamani. Protection and Control of Active Distribution Networks and Microgrids. Ph.D. thesis submitted in The School of Graduate and Postdoctoral Studies, The University of Western Ontario, 2012.

[13] Ozenir Dias, Maria Cristina Tavares. Comparison between traditional single-phase auto reclosing and adaptive technique based on harmonic content measurement. IET Gener. Transm. Distrib., 2017, Vol. 11, Iss. 4, pp. 905–914.

[14] M. Brucoli and T. C. Green, "Fault behaviour in islanded microgrids," in 19th International Conference on Electricity Distribution, 2007, pp. 1-4.

[15] H. Nikkhajoei and R. H. Lasseter, "Microgrid Protection," in Power Engineering Society General Meeting, 2007. IEEE, 2007, pp. 1-6.

[16] H. H. Zeineldin, E. F. El-Saadany, and M. M. A. Salama, "Distributed Generation Micro-Grid Operation: Control and Protection," in Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources, 2006. PS '06, 2006, pp. 105-111.

[17] M. A. Redfern and H. Al-Nasseri, "Protection of micro-grids dominated by distributed generation using solid state converters," in Developments in Power System Protection, 2008. DPSP 2008. IET 9th International Conference on, 2008, pp. 670-674.

[18] E. Sortomme, G. J. Mapes, B. A. Foster, and S. S. Venkata, "Fault analysis and protection of a microgrid," in Power Symposium, 2008. NAPS '08. 40th North American, 2008, pp. 1-6.

[19] E. Sortomme, M. Venkata, and J. Mitra, "Microgrid protection using communication-assisted digital relays," in Power and Energy Society General Meeting, 2010 IEEE, 2010, pp. 1-1.

[20] P. Mahat, C. Zhe, B. Bak-Jensen, and C. L. Bak, "A Simple Adaptive Overcurrent Protection of Distribution Systems with Distributed Generation," Smart Grid, IEEE Transactions on, vol. 2, pp. 428-437, 2011.

[21] M. A. Zamani, T. S. Sidhu, and A. Yazdani, "A Protection Strategy and Microprocessor-Based Relay for Low-Voltage Microgrids," Power Delivery, IEEE Transactions on, vol. 26, pp. 1873-1883, 2011.

[22] M. A. Zamani, A. Yazdani, and T. S. Sidhu, "A Communication-Assisted Protection Strategy for Inverter-Based Medium-Voltage Microgrids," Smart Grid, IEEE Transactions on, vol. 3, pp. 2088-2099, 2012.

[23] S. M. Brahma and A. A. Girgis, "Development of adaptive protection scheme for distribution systems with high penetration of distributed generation," Power Delivery, IEEE Transactions on, vol. 19, pp. 56-63, 2004.

[24] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Modeling of a Centralized Microgrid Protection System and Distributed Energy Resources According to IEC 61850-7-420," Power Systems, IEEE Transactions on, vol. 27, pp. 1560-1567, 2012.

[25] T. S. Ustun, C. Ozansoy, and A. Ustun, "Fault current coefficient and time delay assignment for microgrid protection system with central protection unit," Power Systems, IEEE Transactions on, vol. 28, pp. 598-606, 2013.

[26] M. A. Zamani, T. S. Sidhu, and A. Yazdani, "A communication-based strategy for protection of microgrids with looped configuration," Electric Power Systems Research, vol. 104, pp. 52-61, 2013.

[27] T. Loix, T. Wijnhoven, and G. Deconinck, "Protection of microgrids with a high penetration of inverter-coupled energy sources," in Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium, 2009, pp. 1-6.

[28] S. R. Samantaray, G. Joos, and I. Kamwa, "Differential energy based microgrid protection against fault conditions," in Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES, 2012, pp. 1-7.

[29] M. A. Haj-ahmed and M. S. Illindala, "The influence of inverter-based DGs and their controllers on distribution network protection," in Industry Applications Society Annual Meeting, 2013 IEEE, 2013, pp. 1-9.

[30] E. Casagrande, W. Wei Lee, H. H. Zeineldin, and N. H. Kan'an, "Data mining approach to fault detection for isolated inverter-based microgrids," Generation, Transmission & Distribution, IET, vol. 7, pp. 745-754, 2013.

[31] N. Jayawarna, M. Barnes, C. Jones, and N. Jenkins, "Operating MicroGrid Energy Storage Control during Network Faults," in System of Systems Engineering, 2007. SoSE '07. IEEE International Conference on, 2007, pp. 1-7.

[32] K. Imolauer, et al., "Market and business chances in the EU in the field of renewable energies and energy efficiency," in Telecommunications Energy Conference, 2007. INTELEC 2007. 29th International, 2007, pp. 477-480.

[33] N. Hatziargyriou, et al., "Microgrids," Power and Energy Magazine, IEEE, vol. 5, pp. 78 94,2007.

[34] T. Dagner and P. Strauss, "Laboratory Grid for Distributed Generation," EC ProjectDISPOWER.http://www.iset.unikassel.de/dispower_static/documents/highlight003.pdf, 2003.

[35] Selim Taha, Ustun. Design and development of a communication assisted microgrid protection system. Ph.D. thesis submitted in School of Engineering and Science, Faculty of Health, Engineering and Science, Victoria University; 2013.

[36] Maki K., Repo S., Jarventausta P., General Procedure of Protection Planning for Installation of Distributed Generation in Distribution Network. International Journal of Distributed Energy Resources, Vol. 2, No. 1, January-March 2006, pp. 1-23

[37] Baran ME, Mahajan NRDC. Distribution for industrial system: opportunities and challenges. IEEE Transactions on Industry Applications 2003;39(6)1596–1601.

[38] R. M. Cuzner and G. Venkataramanan, "The status of DC micro-grid protection", IEEE industry applications society annual meeting, pp. 1–8, 2008.

[39] Justo JJ, et al. AC-microgrids versus DC-microgrids with distributed energy resources: a review. Renew Sustain Energy Rev 2013; 24:387–405.

[40] Seyed Amir Hosseini, Hossein Askarian Abyaneh, Seyed Hossein Hesamedin Sadeghi, Farzad Razavi, Adel Nasiri, "An overview of microgrid protection methods and the factors involved", Renewable and Sustainable Energy Reviews 64 (2016) 174–186.

[41] Che L, et al. Adaptive protection system for microgrids: protection practices of a functional microgrid system. IEEE Electr Mag 2014; 2:66–80.

[42] Meghwani A, et al. A new protection scheme for DC microgrid using line current derivative. In: Proceedings of IEEE power & energy society general meeting; 2015. p. 15.

[43] P. M. Anderson and A. A. Fouad, Power System Control and Stability:Iowa University Press, 1977.

[44] Salman SK, Rida IM. Investigating the impact of embedded generation on relay settings of utilities electrical feeders. IEEE Trans Power Deliv 2001; 16:246–51.

[45] J. Lopez et al. Wind Turbines Based on Doubly Fed Induction Generator Under Asymmetrical Voltage Dips. In: IEEE Transactions on Energy Conversion 23.1 (Mar. 2008), pp. 321330.

[46] N. Jenkins et al. Protection guidelines for a microgrid. Final Draft of deliverable DE2 in WP E of project MicroGrids. June 2005.

[47] Al-Nasseri H, Redfern MA. A new voltage-based relay scheme to protect micro-grids dominated by embedded generation using solid state converters. In: Proceedings of the 19th international conference on electricity distribution. CIRED, Vienna; 2007.

[48] Dewadasa M, et al. Protection of microgrids using differential relays. In: Proceedings of the 21st Australasian universities power engineering conference (AUPEC); 2011. p. 1–6.

[49] Dewadasa M, et al. Fold back current control and admittance protection scheme for a distribution network containing distributed generators. IET Gener Transm Distrib 2010; 4:952–62.

[50] Lai K, et al. Comprehensive protection strategy for an islanded microgrid using intelligent relays. In: Proceedings of IEEE industry applications society annual meeting; 2015. p. 1–11.

[51] Miveh MR, et al. Micro-grid protection by designing a communication assisted digital relay. Am J Sci Res 2012:62–8.

[52] W. Bower and M. Ropp, "Evaluation of islanding detection methods for photovoltaic utility interactive power systems," Sandia National Laboratories Photovoltaic Systems Research and Development2002.

[53] Funmilayo HB, Butler-Purry KL. An approach to mitigate the impact of distributed generation on the overcurrent protection scheme for radial feeders. In: Proceedings of IEEE/PES power systems conference and exposition; 2009. p. 1–11.

[54] Tailor JK, Osman AH. Restoration of fuse-recloser coordination in distribution system with high DG penetration. In: Proceedings of IEEE Power and energy society general meeting - conversion and delivery of electrical energy in the 21st century; 2008. p. 1–8.

[55] Hatziargyriou, N. (Ed.). (2014). Microgrids: architectures and control. Wiley/IEEE Press.

[56] Kumara JRSS, et al. Over current protection coordination of distribution networks with fault current limiters. In: Proceedings of IEEE power engineering society general meeting; 2006.

[57] Shahriari SAA, et al. Minimizing the impact of distributed generation on distribution protection system by solid state fault current limiter. In: Proceedings of IEEE PES transmission and distribution conference and exposition; 2010. p. 1–7.

[58] Chabanloo RM, et al. Overcurrent relays coordination considering transient behavior of fault current limiter and distributed generation in distribution power network. IET Gener Transm Distrib 2011; 5:903–11.

[59] Kai-Hui Z, Ming-Chao X. Impacts of microgrid on protection of distribution networks and protection strategy of microgrid. In: Proceedings of international conference on advanced power system automation and protection (APAP); 2011. p. 356–359.